EXPERT SYSTEM DEVELOPMENT FOR REFRACTORY BRICK MANUFACTURING PROCESS

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DECEMBER, 2001

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A Thesis submitted
in partial fulfilment of the requirement
for the degree of

MASTER OF TECHNOLOGY

By
Sqn Ldr PA Patil

To the

Department of Electrical Engineering
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

December 2001

I.I.T. 28/12/01

CERTIFICATE

This is to certify that the work contained in this thesis entitled **"Expert System Development For Refractory Brick Manufacturing Process"**, by Sqn Ldr PA Patil, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree

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Dec 01

ACKNOWLEDGEMENT

I express my profound gratitude to Dr Prem Kumar Kalra for his day-to-day guidance and enduring supervision throughout this programme. Besides providing academic guidance he was always there to provide inspiring ideas, motivation and moral support. I would also like to thank him for the complete freedom he provided to me for this work and for the excellent facilities in the lab. But for his able guidance, it would have been very difficult for me to work in the field of expert system and fuzzy logic to achieve what I could in this short span of time

My special thanks go to Major Mohan Kumar for his invaluable ideas and help provided during the stay at IIT I also thank Prasanth, Madhav Krishna, Major Jayesh, Major Rajesh Vaid, Saleem, Manoj and Shankar for their co-operation and maintaining of a cordial and conducive environment in the lab

My thanks also go to Dr. PK Ghosh, Mr. P Barua and Mr. SK Nandy for introducing me to a totally new field of Steel Manufacturing and imparting knowledge on the subject. This work would not have completed without their help, contribution and valuable discussions from time to time.

And last but not the least I am grateful to my family, who gave me full wholehearted support throughout my course and adjusted to my unearthly routines during the thesis work.

ABSTRACT

Converters are a vital link in a steel plant and the plant productivity depends largely on the trouble free run of this steel-making vessel Dramatic improvements have been made in converter life for a variety of reasons, which include, process developments, and developments in lining technology. Magnesia-Carbon refractories are one of the most researched subjects worldwide. Over the past years Rourkela Steel Plant, with the R & D centre for Iron and Steel, Ranchi has been successful in improving the lining life of its converters from 300 heats to 1000 heats, with considerable reductions in refractory cost per tonne of steel, and reductions in maintenance costs.

To improve and sustain the lining life of converters an expert system is developed to predict various parameters and properties of the Magnesia-Carbon Bricks using the Flex software acquired by Steel Authority of India for this purpose. Two modules are developed. One uses rules formulated from the advice of experts while the other uses rules derived out of plant data. Inductive Decision Tree (ID3) algorithm for rule generation is also used and discussed. The results from both the modules are compared with the result of Matlab Fuzzy Toolbox. Tools like Microsoft Bayesian Network and Multivariate Adaptive Regression Splines have been used in validation of rules, checking the variable importance and finding effect of each variable on others

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LIST OF ABBREVIATIONS

BOF	-	Basic Oxygen Furnace
MgO-C	-	Magnesia Carbon
LDBP	-	Lead Dolomite Brick Plant
SAIL	-	Steel Authority of India
RDCIS	-	Research and Development Center for Iron and Steel
RSP	-	Rourkela Steel Plant
ID3	-	Inductive Decision Tree
MARS	-	Multivariate Adaptive Regression Splines
BD	-	Bulk Density
KSL	-	Knowledge Specification Language
FLINT	-	Fuzzy Logic Inferencing Toolkit
FAM	-	Fuzzy Associative Memory
BBN	-	Bayesian Belief Network
CCT	-	Combustion Chamber Temperature
GHDT	-	Grain Heater Drum Temperature
RT	-	Retention Time in Grain Heater
GT	-	Grain Temperature
MT	-	Mixer temperature
MTM	-	Mixing time
MIX	-	Mix temperature
ST	-	Storage time
ROLLS	-	Number of rolls
PMT	-	Press Mix Temperature
FP	-	Forming pressure
PQ	-	Pitch quantity
GQ	-	Graphite quantity
GBD	-	Green Bulk Density
TBD	-	Tempered Bulk Density
CCS	-	Cold crushing strength
CP	-	Coked porosity

(Contd…)

List Of Abbreviations (Contd.)

HMOR	-	Hot Modulus of rupture
SCR	-	Slag corrosion Resistance
OR	-	Oxidation Resistance
RC	-	Retained Carbon
MP	-	Metal Powder
CHP	-	Chemical Purity
MSBNX	-	Microsoft Bayesian Networks
TS	-	Tempering Status

UNITS OF MEASUREMENTS

The following units of measurements are used throughout the text

CCT	-	Combustion Chamber Temperature (^{0}C)
GHDT	-	Grain Heater Drum Temperature (^{0}C)
RT	-	Retention Time (minutes)
GT	-	Grain Temperature (^{0}C)
MT	-	Mixer temperature (^{0}C)
MTM	-	Mixing time (minutes)
MIX	-	Mix temperature (^{0}C)
ST	-	Storage time (minutes)
ROLLS	-	Number of rolls (number)
PMT	-	Press Mix Temperature (^{0}C)
FP	-	Forming pressure (Kg/cm^2)
PQ	-	Pitch quantity (%)
GQ	-	Graphite quantity (%)
GBD	-	Green Bulk Density (gms/cc)
TS	-	Tempering Status (^{0}C)
CCS	-	Cold crushing strength (Kg/cm^2)
CP	-	Coked porosity (%)
HMOR	-	Hot Modulus of rupture (Kg/cm^2)
SCR	-	Slag corrosion Resistance (%)
OR	-	Oxidation Resistance (mm)
RC	-	Retained Carbon (%)
MP	-	Metal Powder (%)
CHP	-	Chemical Purity (scaled in range 0-100)

CHAPTER 1
INTRODUCTION

1.1 Background

Basic Oxygen Furnace (BOF) is the leading route for steel making worldwide. BOF, commonly known as Converter, is a vital link in a steel plant and the plant productivity depends largely on the trouble free run of the steel-making vessel. With the advent of several maintenance practices, it is now a well-established fact that a combination of High Quality bricks and continuous monitoring of operating parameters with planned maintenance schedule engineer the campaign life of a Converter. Magnesia-Carbon refractories are established as a universal choice for the converter. Magnesia-Carbon refractories is one of the most researched subjects worldwide with the help of the state of the art R&D facility and the extensively application experience.

Pitch bonded magnesia carbon (MgO-C) bricks are manufactured at LDBP at Rourkela Steel Plant in a joint project with Research and Development Center for Iron and Steel (RDCIS), Ranchi. These bricks essentially constitute of magnesia grains and natural graphite As there is no mutual reaction between the two main components of the material, a liquid binder like pitch or resin is used to manufacture bricks from these materials. At high temperature, carbon network is produced from this binder to produce the required binding.

Manufacturing of MgO-C brick involves preparation of a batch with optimum granulometry, mixing of the two main components in particulate form with liquid binder, compaction under appropriate pressure to get optimum bulk density and subsequent heat treatment.

1.2 Thesis Objective

The magnesia carbon bricks manufactured and used at RSP presently have a lining life of around 900 to 1000 heats. Strong competitive market conditions have set a demand for high performance refractories. The main aim of this work was to develop an expert system to improve the lining life of converter, improve and sustain the properties of bricks and assist the staff of RSP with the vast knowledge of those experts from whose input the system was developed. The system was designed to provide help in prediction of various parameters and assisting in controlling of process parameters.

1.3 Thesis Organization

The basic plant process is explained in chapter 2. In addition to plant process, various properties of bricks have been discussed to give a broad oversight on importance of material composition and process parameters in manufacturing process of bricks. Chapter 3 discusses the Expert System software acquired from Logic Programming Associates and the other tools like the ID3 Algorithm, Bayesian Networks and Multivariate Adaptive Regression Splines Generation of rules has been discussed in chapter 4. The chapter also deals with building decision trees using ID3 algorithm Chapter 5 deals with the design of fuzzy expert system for the brick manufacturing plant In this two methods are used. One system uses the rules formulated from the expert advice whereas the other system uses the rules as derived directly from data. The results from both the methods are discussed and further these results are compared with the results obtained using Matlab. Chapter 6 discusses validation of rules by use of Bayesian network and probabilistic study of effect of various parameters on final output. Also the result obtained using Multivariate Adaptive Regression Splines (MARS) is discussed. Chapter 7 provides the summary of the work with the future scope for expansion and use of this system.

CHAPTER 2

MAGNESIA CARBON BRICK MANUFACTURING PROCESS & PROPERTIES

2.1 Introduction

This chapter gives a broad outline of the manufacturing process of Magnesia Carbon Bricks at Rourkela Steel Plant. The main aim of the chapter is to help in understanding the brick making process so that the logic used to develop the expert system can be correlated with the work done. Materials and brick properties are also discussed to give a broad insight on the effect they cause on the final output. However as the process in itself does not form part of thesis, the details are not presented.

2.2 Brick Manufacturing Process

The main raw materials used are lumps of seawater magnesia sizing in the range of 0 to 25 mm, natural graphite in powdered form and pitch in liquid form. The basic process of Brick Making [1] can be understood easily through the flowchart given in figure 2.1.

For Granulometry lump Magnesia of size 0-25 mm is stored in Rotary Kiln Bunker and fed to Brick Plant Bunker for crushing and Grinding. After crushing different fractions are obtained using impact mills. The fine fractions of Magnesia are generated using Vibro Mill. These fractions of 5-8, 3-5, 1.6-3, 0.5-1.6 mm (coarse fractions), 0-0 5 and 0-0 1 mm (fine fractions) are then mixed in a fixed proportion to form a batch of 1000 Kg during the plant process. Fine fractions of magnesia are not heated and are kept in a fine hopper along with powdered graphite. The coarse grain fractions from coarse hoppers are first fed to the grain heater drum in the combustion chamber, where they are heated to a high temperature. After heating is completed the coarse grains are discharged into a mixer. After this molten pitch is added to the coarse grains in the mixer and mixed with the pitch coated coarse grains for 5 to 7 minutes to get uniformly coated mix. The contents of fine hopper are now discharged into the mixer and further mixing

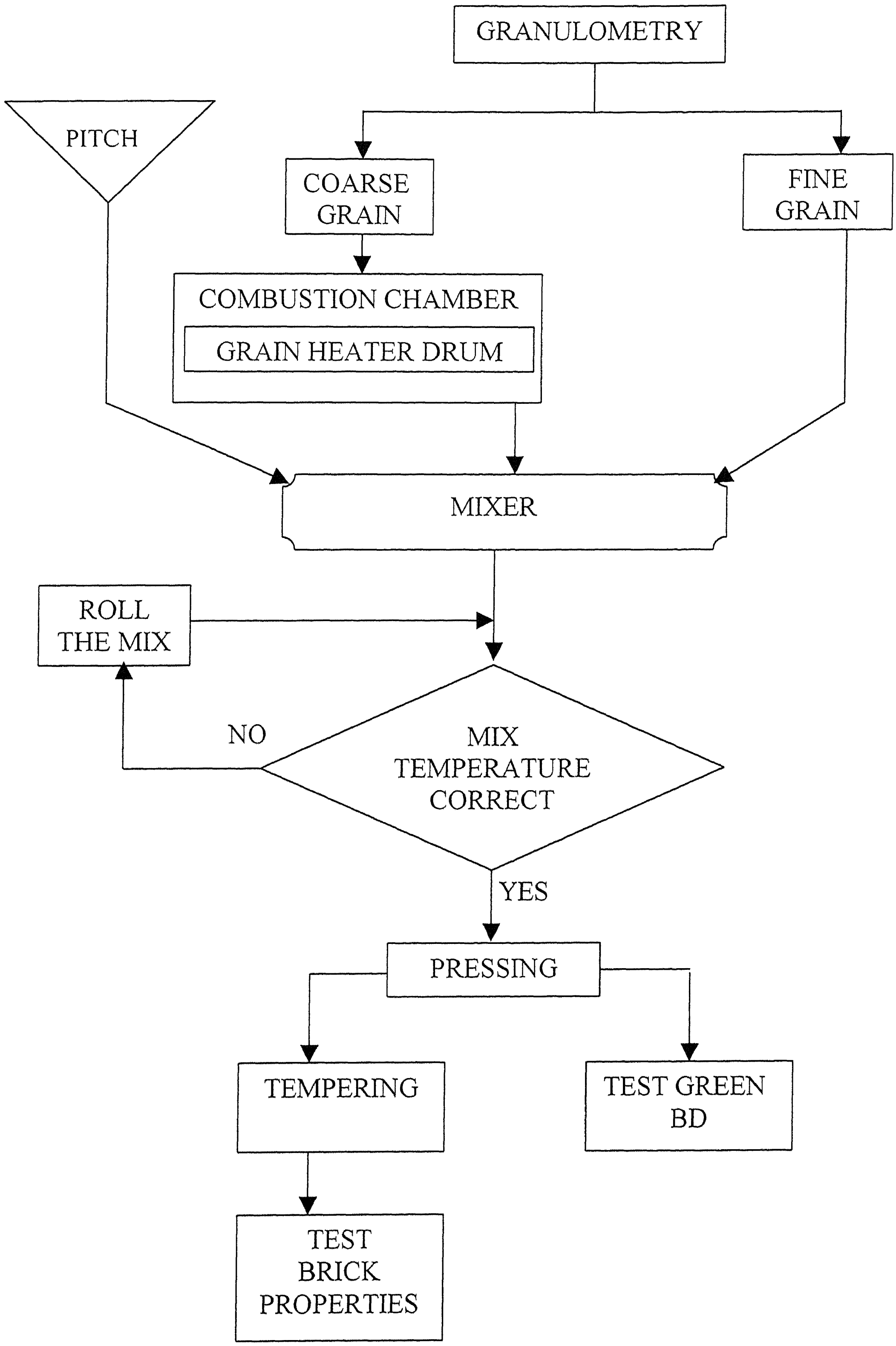

Figure 2.1: Flowchart of Brick Manufacturing Process

takes place. The mix after some time is checked for consistency visually and a few liters of pitch is further added if required Hot mix is discharged into the mix box and the mix is kept for 30 to 90 minutes for natural cooling depending on the temperature of the mix. If the mix temperature is found to be higher it is charged into the standby press hopper and cooled to the desired temperature by rolling using the conveyer of the press. Then it is charged into the operating press hopper for pressing. After coming out of the press system the bricks are stacked in the tempering kin pallets. Hot bricks kept in tempering kiln pellets are stacked in the tempering kiln car and pushed into the kiln. After the tempering is completed the bricks are cooled and stored in batches.

2.3 Raw Materials and Properties

- **Magnesia**· As this is a major constituent its chemical and physical properties are very important to achieve a higher lining life of the converter. Very high purity MgO grains with bigger crystal size are desirable The type, quantity and relative proportions of chemical impurities present in magnesia have a fundamental effect on slag resistance and high temperature mechanical properties. Another major role is played by the various crystal sizes of magnesia used during the brick making process. These proportions are fixed quantities of different sized crystals, which have been obtained after thorough research and tests to get a good green bulk density of brick. As high purity synthetic dead burnt magnesia produced from seawater is used, the effect of various impurities e g. SiO_2, CaO, Al_2O_3, Fe_2O_3 and B_2O_3 on the hot modulus of rupture strength is present. Research is still on at RDCIS to control these impurities to the required amounts so as to use these impurities to the benefit of obtaining a brick having a long lining life.
- **Graphite**: The critical thermo-mechanical properties of MgO-C bricks are largely controlled by graphite. Graphite is also responsible for high slag corrosion resistance. The problem associated with graphite is that it oxidizes at high temperature. Slag resistance, oxidation resistance and the thermo-mechanical properties depend on brick porosity, graphite content and the graphite flake size. Flake structure and grain size distribution of graphite is of decisive importance for

the press ability and compaction the magnesia carbon bricks as well as oxidation resistance.

- **Binder**· For manufacturing of magnesia carbon bricks, pitch is used as binding material. Pitch is solid at ambient temperature and therefore elaborate melting, storage and handling facilities are required. Also use of pitch requires high temperature mixing and pressing. Carbon generated after pyrolysis of pitch can be converted to graphite. As pitch is thermoplastic in nature it melts on heating and then after polymerization it becomes hard and brittle Thus pitch should be used in optimum quantity

2.4 Important Parameters In Brick Making Process

- **Granulometry:** Grain size distribution finalized to achieve a high bulk density and cold crushing strength while lower coked porosity and desired level of retained carbon is shown below for a single batch.
  - 5-8 mm ....150 Kg
  - 3-5 mm ....230 Kg
  - 1.6-3 mm ....170 Kg
  - 0.5-1 6 mm .... .150 Kg
  - 0-0.5 mm .. ..100 Kg
  - 0-0.1 mm . .. .200 Kg
- **Graphite Quantity:** For each batch of 1000 Kg the optimum quantity of graphite used for the best results is fixed at 50 Kg.
- **Pitch Quantity:** Pitch is used in molten state. It is also added in fixed proportion of 44 liters per batch. It is desired that the quantity of pitch so added does not vary from the specified value.
- **Combustion Chamber Temperature:** The chamber is heated by burning of the waste gases from other divisions of the steel plant. The coarse grain is passed through the chamber with temperature varying widely from 250 to 550 degree centigrade. As the grains at the start are at room temperature, the Combustion

Chamber temperature actually drops as the grains get heated. The hot gas from the combustion chamber is further circulated to the mixer.

- **Grain Heater Drum Temperature:** At this stage the coarse grains are heated to the required temperature in an inner rotating drum to be maintained at 450 to 500 degrees. However due to manual control of the temperature of combustion chamber, gas impurities and change of shifts of operators the temperature of inner drum heated by the hot gas circulating between outer and inner drum generally varies out of this range from 300 to as high as 700 degree centigrade The main aim in this stage is to increase the temperature of coarse grains so that they can be fed to mixer.
- **Grain Heater retention time:** This is the time for which the grains will be heated in the grain heater drum. This is one important parameter that is directly controlled by the operators on duty to achieve the requisite grain temperature. Optimally as given in plant specifications this time theoretically should vary from 1.5 to 2.5 minutes. However from the knowledge acquired from experts and the plant data available this time generally varies from 3 to 9 minutes.
- **Grain Temperature:** Though this is one of the most important parameter there does not exist any means to check the temperature of grains in any of the batches at plant The knowledge acquired is absolutely fuzzy and is included in this work on advice from experts
- **Mixer Temperature:** The hot coarse grains are fed to the mixer being continually heated form the circulating gas where the fines and graphite in powdered form along with the molten pitch are added and mixed to get a consistent mixture (hereafter called mix). This varies from 100 to 140 degrees.
- **Mixing Time:** The consistency of mix plays an important role. The time in the mixer varies from 4 to 20 minutes and is controlled by operators who evaluate the mix condition by experience. When the desired consistency is achieved the mix is poured out from the mixer in a container.
- **Mix Temp:** The desired temperature of mix is 120 to 130 degrees centigrade however due to various factors deviations exist from batch to batch. A thermal sensor in the mixing drum picks up the Mix temperature. In case the Mix

temperature is too low, the mix is discharged back to grain heater drum for reheating.

- **Storage Time:** Generally the mix temperature obtained is above the specified limits of 120 to 125 degree centigrade and is allowed to cool down for some hours.
- **Rolling of Mix:** In case the temperature of mix is too high, storing the mix for long times does not help as the temperature drops by maximum of 4 degrees per hour. In this case the mix is taken to a certain height using conveyer belts and dropped in the storage drum for faster cooling One such cycle hereafter is called one roll. Multiple rolls can be performed to achieve the desired mix temperature.
- **Press Mix Temperature:** This is the temperature of the mix at the time of discharging in the moulds for making of bricks. This temperature as seen from the data varies from 110 to 130 degrees in most of the cases.
- **Forming Pressure:** This is the pressure set for the press system and varies from 190 to 210 bars.
- **Green Bulk Density:** Bulk density is defined as the total mass of a body divided by the bulk volume. The bulk volume includes the volume of solid particles, the volume of any temporary additives and liquid present, and the volume of empty pore space. This is one of the most important parameter and if this parameter is achieved in a range of 3.05 to 3.15 gms/cm^2, the main aim of achieving higher lining life is by and far achieved.
- **Tempered Bulk Density:** This is the Bulk density achieved after tempering. Tempering (Curing) is done at a temperature of 300 to 350^0 C.
- **Cold Crushing Strength:** Cold crushing strength of refractory bricks is the gross compressive stress required to cause fracture. Refractories are normally strong in terms of compressive strength - usually five times the tensile strength as reflected in the Cold Crushing Strengths With optimum green BD, the CCS achieved is 300 to 450 Kg/cm^2.
- **Hot Modulus of Rupture:** The value of HMOR is seen to vary form 30 to 50 Kg/cm^2 when measured in appropriate conditions. The plant was unable to supply

the data and the fuzzy membership functions were formed from the advice of the experts. Higher the HMOR better the lining life.

- **Coked Porosity:** Coked porosity generally varies from 10.82 to 15.25% The bricks with lower retained carbon showed lower coke porosity. Batch data is not available.
- **Carbon Content (Retained Carbon):** This indicates variation in quantity of graphite added and also the quantity of pitch added during mixing This varies from 4 84 to 7 4% Batch data is not available.
- **Metal (Aluminum) Powder:** The amount of metal powder added is still in evaluation phase and presently trials are conducted with 0 5 to 2%. Batch data is not available
- **Oxidation Resistance:** This is the oxidized portion depth measured in millimeters. It varies from 7 to 11 mm.
- **Chemical Purity:** The magnesia may be of natural, seawater or fused grade. Based on their performance standard, rating has been done. Fused magnesia of high quality has been rated the highest The present quality of seawater magnesia in use at RSP as medium and so on. Rating is done on a scale from 0-100.
- **Slag Corrosion Resistance:** The bricks with higher content of graphite show lower corrosion index and vice versa. It corrosion index varies from 70 to 120 % in normal conditions.

CHAPTER 3

EXPERT SYSTEM SOFTWARE FROM LPA AND TOOLS

3.1 Introduction

Expert systems [2] (or knowledge-based systems) allow the scarce and expensive knowledge of experts to be explicitly stored into computer programs and made available to others who may be less experienced. They range in scale from simple rule-based systems with flat data to very large scale, integrated developments taking many person-years to develop. They typically have a set of **if-then** rules that forms the knowledge base, and a dedicated inference engine, which provides the execution mechanism. This contrasts with conventional programs where domain knowledge and execution control are closely intertwined such that the knowledge is implicitly stored in the program. This explicit separation of the knowledge from the control mechanism makes it easier to examine knowledge, incorporate new knowledge and modify existing knowledge.

3.2 Flex Expert System Toolkit

The Steel Authority of India acquired this toolkit from Logic Programming Associates. Flex [3] is a language specially designed for the development of Expert Systems. It is implemented in Prolog but uses simple sentences in English unlike a programming language. This is a feature of its Knowledge Specification Language (KSL). Flex can carry out most of the procedures needed to build knowledge-based systems.

3.2.1 Flex program

A Flex program is a collection of KSL statements. Flex being implemented in Prolog extends the traditional Prolog environment with access to the underlying Prolog. It contains many constructs ideal for building knowledge-based systems (frames, instances, rules, relations, groups, questions, answers, demons, actions, functions) Flex can

recognize and compile both Flex (KSL files) and Prolog (PL files). If something can't be done in Flex, then it can generally be accomplished in Prolog. With the combination of Flex and Prolog one can fine tune and enhance the built-in behaviour mechanisms to suit ones own specific requirements.

3.2.2 Rules

Knowledge and expertise can be expressed as **if-then** rules, where the **if** part contains the pre-conditions and the **then** part the action or conclusion. Rules are linked or chained together by an inference engine, which matches the conditions of one rule to the conclusions of another This engine can chain either forwards or backwards.

- **forward chaining** - to go from existing data and a set of rules to produce new data. This is often referred to as data-directed reasoning and indicated by the keyword **rule.**
- **backward chaining** - to prove a particular goal or hypothesis by testing for specified data. This is often referred to as goal-directed reasoning and indicated by the keyword **relation.**

The main thrust of the flex rule engine is forwards. In forward chaining we start with an initial set of rules and a database of facts. The Program then cycles through the rulebase looking for a rule whose **if** conditions can be satisfied and add it to the conflict set. A rule is then selected from this conflict set to fire, which involves executing its **then** part. This often changes the fact base, which means that different rules may now fire, so giving a different conflict set. It is also possible to update the order of the rule agenda ready for the next cycle. This cycle is repeated until empty conflict set (no rules will fire) is produced, or a specified early-termination condition is met. Rules must have a name, condition(s) to be satisfied and concluding action(s) to perform if the rule is fired.

3.2.3 Rulesets

The ruleset construct allows us to group rules together to form stratified rule bases and as well as control the forward-chaining engine. Within a ruleset we can specify·

a) The selection algorithm to be used to determine which rule is selected when the conditions of more than one rule succeed
b) The update algorithm to be used to update the rule agenda after a rule has been fired.
c) The termination conditions to determine how to halt the session early (rather than run-out of rules to fire)

The ruleset also supports other options like the ability to nominate failure and initiation procedures to be associated with that forward-chaining session. Large rule bases can be grouped into discrete rulesets and dynamically loaded into or out of the agenda

3.3 FLINT toolkit

FLINT stands for **F**uzzy **L**ogic **IN**ferencing **T**oolkit [4]. It is a fuzzy logic inferencing system that uses fuzzy logic technology and fuzzy rules available within the programming environment. The advantages of fuzzy logic expert systems compared to non-fuzzy expert systems are that they typically require fewer rules, need fewer variables, use a linguistic rather than a numerical description, and can relate output to input for any device without needing to understand the device's inner workings.

3.3.1 Fuzzy Logic

Fuzzy logic is a superset of conventional Boolean logic with extensions to cater for imprecise information. Fuzzy logic permits vague information, knowledge and concepts to be used in an exact mathematical manner. Words and phrases such as 'High', 'medium', 'very high', 'quite low', 'not very low', 'very very very high' are used to describe continuous, overlapping states [5] This enables qualitative and imprecise reasoning statements to be incorporated within rule-bases so producing simpler, more intuitive and better-behaved models. Fuzzy logic is based on the principle that every crisp value

belongs to all relevant fuzzy sets to various extents, called the degrees of membership. These range from 0 (definitely not a member) to 1 (definitely is a member) with values between generated by a membership function This contrasts with conventional, boolean logic, where membership of a set is either false or true, i.e. 0 or 1. This graduation from zero to one enables us to smooth out and overlap the boundaries between sets. Unlike boolean logic [5] where sets are mutually exclusive, fuzzy logic allows crisp values to belong to more than one fuzzy set. This means that whereas in a crisp system, only one rule might be fired and used, in a fuzzy system all rules are used, with each having some influence on the resulting output This is more of a consensus approach to expert systems.

In boolean logic, to see if a temperature is 'high', we would choose a point, say 100, which separates 'high' from 'not high' and then perform a mathematical comparison for any given speed which would return either true (1) or false (0). For instance, the crisp value 99 is less than 100 and will return a membership value of 0 with respect to the set of high temperatures The value 101 being greater than 100 will return a membership value of 1 A weakness of this approach is that it does not reflect that 99 is only just below the cut off point whereas 15 is well below. Applying rules that refer to high and not high will give the same behaviour for objects travelling at 15 and 99, but very different behaviour for speeds of 99 and 101. In certain situations this may be desirable (maybe breaking a speed limit), but often, because knowledge is inexact and cut-off points are arbitrary, this behaviour is undesirable (e g. rules of safety for driving).

3.3.2 The features of FLINT

FLINT supports the concept of fuzzy variables (like pressure, temperature) and the concept of fuzzy qualifiers (hot, high, low, fast). Applying a qualifier to a fuzzy variable generates a fuzzy set. For each fuzzy set there is a membership function relating crisp to fuzzy values, and which is defined in terms of its shape and location. FLINT supports various standard shapes (trapezoids, triangles) as well as any user-defined shape. For each of these lines can be specified as either straight or curved. FLINT also supports the concept of fuzzy modifiers (very, extremely, not very), commonly referred to as linguistic hedges. These affect the membership function by intensifying (concentrating) or spreading (diluting) its shape.

Fuzzy rules define relationships between different fuzzy sets as if-then rules. In FLINT, these rules are expressed using a simple, uncluttered syntax. Furthermore, they can be grouped into matrices, commonly known as fuzzy associative memory (FAM). In fuzzy reasoning over sets there are standard operations such as union and intersection These operations can be defined in terms of simple mathematical operations such as maximum, minimum, addition, strengthening (difference between sum and product). FLINT supports various mathematical operators that can be combined to implement numerous strategies including min-max, additive, and strengthening. The final stage of a fuzzy evaluation is the conversion back from fuzzy membership values to crisp values for the output variables, which is referred to as defuzzification. FLINT supports two standard defuzzifiers, the centroid method that is based on the centre of gravity, and the peak method that is based on the highest fuzzy value.

3.3.3 Conflict Resolution

Conflict resolution [2] is a more sophisticated and computationally expensive selection scheme whereby the "best" rule is always selected. A conflict occurs when more than one rule can be fired (i.e. the **if** conditions of more than one rule are satisfied). This conflict is then resolved by choosing the rule with the highest score. In the event of a tie the first is chosen. This scheme certainly allows far more control over the selection phase, but at a high cost. The "best" rule can only be chosen if every rule is considered. For example, if the agenda contains 1000 rules then all of them need to be tested, even though the best rule may be the *5th* rule in the sequence We do not know for certain that it is the best rule until the other 995 have been considered.

3.4 The ID3 Algorithm

ID3 algorithm [2], [6] builds a decision tree from a fixed set of examples. The resulting tree is used to classify future samples. The example has several attributes and belongs to a class (like high, medium or low). The leaf nodes of the decision tree contain the class name whereas a non-leaf node is a decision node. The decision node is a test for attribute, with each branch (to another decision tree) being a possible value of the attribute. ID3 uses information gain to help it decide which attribute goes into a decision

node The advantage of learning a decision tree is that a program, rather than a knowledge engineer, elicits knowledge from an expert. ID3 algorithm derives its classes from a fixed set of training instances The classes created by ID3 are inductive, that is, given a small set of training instances, the specific classes created by ID3 are expected to work for all future instances. The distribution of the unknowns must be the same as the test cases. Induction classes cannot be proven to work in every case since they may classify an infinite number of instances. It is also possible that the ID3 algorithm may misclassify data In a set of records, each record has the same structure, consisting of a number of attribute/value pairs One of these attributes represents the goal of the record The problem is to determine a decision tree on the basis of answers to questions about the non-goal attributes predicting the value of the goal attribute correctly.

3.4.1 Attribute Selection

To select the best attribute, ID3 uses a property, called information gain. The Attributes Entropy measures the amount of information in an attribute. Gain measures how well a given attribute separates training examples into targeted classes. The one with the highest information (information being the most useful for classification) is selected. The formula for the entropy of any given attribute, A_k, is given as

$$H(C \mid A_k) = \sum_{j=1}^{M_k} p(a_{k,j}) * \left[-\sum_{i=1}^{N} p(c_i \mid a_{k,j}) * \log_2 p(c_i \mid a_{k,j}) \right] \qquad \ldots\ldots(3.1)$$

where,

$H(C|A_k)$ = entropy of the classification property of attribute A_k

$p(a_{k,j})$ = probability of attribute k being at value j

$p(c_i| a_{k,j})$ = probability that the class value is c_i when attribute k is at its jth value.

M_k = total numbers of attributes A_k; $j = 1,2,\ldots,M_k$

N = total number of different classes or outcomes; $i = 1,2,\ldots,N$.

K = total numbers of attributes; $k = 1,2, \ldots,K$

3.4.2 Decision Tree Algorithm

ID3 algorithm can be summerised as:

- For each attribute, compute its entropy with respect to the target atrribute.
- Select the attribute (say X) with lowest entropy
- Divide the data into separate sets so that within a set, X has a fixed value
- Build a tree with branches:
    - if X=x1 then . (subtree1)
    - if X=x2 then ... (subtree2) etc. .
- For each subtree, repeat this process from start.
- At each iteration, one attribute gets removed from consideration. The process stops when there are no attributes left to consider, or when all the data being considered in a subtree have the same value for the conclusion.

3.5 Multivariate Adaptive Regression Splines

MARS [7] is an innovative and flexible modeling tool that automates the building of accurate predictive models for continuous and binary dependent variables. The MARS toolkit was used in this work to check the relationship shown between the various inputs, the variable importance & the possible interactions. A regression model can be used for predictive modeling and data mining because of the following characteristics.

- A regression model predicts the outcome variable by forming a weighted sum of the predictor variables in such a way that the predicted outcome changes in a smooth and regular fashion as the inputs change.
- This is in contrast to a decision tree where a small change in a predictor could either move a prediction to a different node in the tree or result in no change in the prediction at all.
- When scoring a database, regression models typically produce unique scores for each record. Decision trees assign the same score to all records arriving at a specific node; thus, the smaller the decision tree, the fewer the number of unique scores assigned.

MARS essentially builds flexible models by fitting piecewise linear regressions [7], that is, the nonlinearity of a model is approximated through the use of separate regression slopes in distinct intervals of the predictor variable space. An example of a piecewise linear regression is shown in figure 3 1 below.

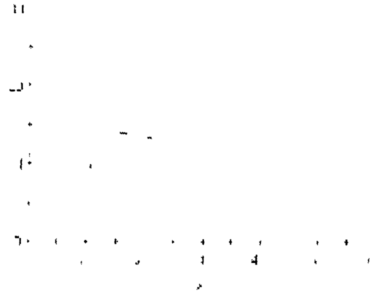

Figure 3.1: A piecewise linear regression

The slope of the regression line is allowed to change from one interval to the other as the two-knot points are crossed The variables to use and the end points of the intervals for each variable are found via a fast but very intensive search procedure In addition to searching variables one by one, MARS also searches for interactions between variables, allowing any degree of interaction to be considered

3.6 Bayesian Belief Network

The belief network [8] is a `causal reasoning' tool that has found many uses in a wide variety of applications, and is now the mainstay of the field of uncertain reasoning. A Bayesian Belief Network (BBN) is a graphical network that represents probabilistic relationships among variables. BBNs are based on the laws of probability, and in particular conditional and Bayesian probability theory. BBNs enable reasoning under uncertainty and combine the advantages of an intuitive visual representation with a sound mathematical basis in Bayesian probability. With BBNs, it is possible to articulate expert beliefs about the dependencies between different variables and to propagate consistently the impact of evidence on the probabilities of uncertain outcomes.

In a joint probability distribution as the number of variables grows, it becomes difficult and complicated to specify probabilities for each atomic event. By using a belief

network, one can represent the dependence between variables and give a concise specification of the joint probability distribution Besides more efficient representation and computation, an additional benefit of using conditional probability and belief networks over a joint probability distribution is that information is represented in a more understandable and logical manner, making construction and interpretation much simpler.

3.6.1 Advantages using BBN

There are many advantages of using BBNs, the most important being the ability to represent and manipulate complex models that might never be implemented using conventional methods. Another advantage is that the model can predict events based on partial or uncertain data Because BBNs have a rigorous, mathematical meaning there are software tools that can interpret them and perform the complex calculations needed in their use The advantage of describing a probabilistic argument via a BBN, compared to describing it via mathematical formulas and prose, is that the BBN represents the structure of the argument in an intuitive, graphical format. The main use of BBNs is in situations that require statistical inference in addition to statements about the probabilities of events. The user knows some evidence, that is, some events that have actually been observed, and wishes to infer the probabilities of other events, which have not as yet been observed. Using probability calculus and Bayes theorem it is then possible to update the values of all the other probabilities in the BBN. This is called propagation. Bayesian analysis can be used for both 'forward' and 'backward' inference.

3.6.2 Belief network construction

Before evidence can be added and beliefs extracted from a BBN, it must first be created. The initial design of belief networks generally requires the help of `expert' in the area being modeled, to specify the correct causal relationships and conditional probabilities. The simplified steps for building and using a belief network are summarized by the flowchart given in figure 3.2.

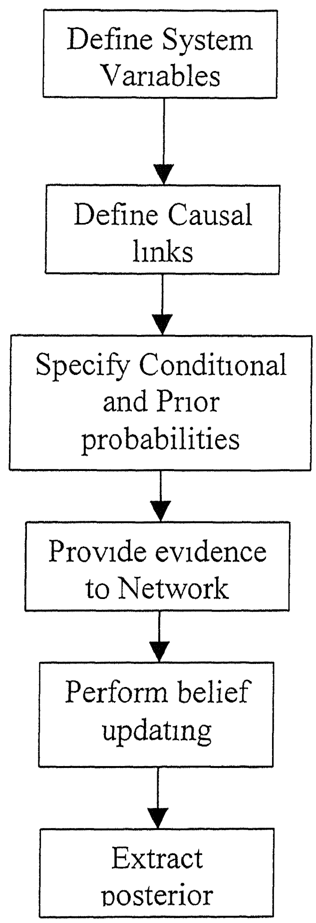

Figure 3.2 Belief Network Creation

CHAPTER 4

KNOWLEDGE REPRESENTATION OF PLANT PROCESS VIA RULE BASED SYSTEM

4.1 Introduction

The most popular mode of knowledge representation within expert systems is through use of rules [9]. Knowledge and expertise can be expressed as IF-THEN rules, where the IF part contains the pre-conditions and the THEN part the action or conclusion. Rule based knowledge representation is used for the expert system developed for lining of converters for the following reasons:

- Widespread availability of rule based expert system shell permits the knowledge engineer to focus attention on critical phases of development of expert system on the available knowledge base.
- Time required to develop expert system is minimized.
- Learning through rule base is easy and fast.
- Rule bases can be easily modified.
- Validation of rule bases is simple and a number of tools are available for the same.
- And finally Flex and Flint expert system acquired by SAIL, India for the purpose of development of system package employ rule bases.

In developing the expert system two different sets of rule bases were formed to achieve the results.

(a) Rule Base from Expert Advice: The rule base was formulated on the knowledge acquired from the experts located at RDCIS, Ranchi and interaction with personnel at various levels at RSP, Rourkela. The knowledge was acquired during visit at the factory premises from operators at the lowest level onwards to shop assistants and managers.

(b) Data based: This rule base was formed with the data made available from plant. The rules were formulated by assigning symbolic values to the various attributes as per the numeric values taken by them

4.2 Rule Base From Expert Advice

As the available data at the start of project was hardly a few lines the development of expert system was started with rule base made on the advice of experts. The most important result is to achieve the Green Bulk Density of the bricks within the specified limits. In the plant the important parameters which effect the Green Bulk Density are listed below:

- Combustion Chamber Temperature (CCT)
- Grain Heater Drum Temperature (GHDT)
- Retention Time in Grain Heater (RT)
- Grain Temperature (GT)
- Mixer temperature (MT)
- Mixing time (MTM)
- Mix temperature (MIX)
- Storage time (ST)
- Number of rolls (ROLLS)
- Press Mix Temperature (PMT)
- Forming pressure (FP)
- Pitch quantity (PQ)
- Graphite quantity (GQ)

The important properties of the MgO-C bricks are listed below:

- Green Bulk Density (GBD)
- Tempered Bulk Density (TBD)
- Cold crushing strength (CCS)
- Coked porosity (CP)

- Hot Modulus of rupture (HMOR)
- Slag corrosion Resistance (SCR)
- Oxidation Resistance (OR)

As the number of input parameters was high and each of the attributes above took values like very high, high, medium, low and very low the number of rules to get the green bulk density would be enormous. Also the effects of parameters like Combustion Chamber temperature, Grain heater drum temperature, Mixer temperature and so on will not affect the Green BD directly. The affect of these parameters is already reflected on certain parameters in-between the plant process. Thus the rule sets were formulated accordingly. The various rule sets formed are discussed below.

(a) Grain Temperature: Grain temperature is the temperature of the coarse grains when being fed to the mixer In the plant their does not exists any direct means to measure this temperature. The temperature has to be measured manually by using a thermal sensor attached to a rod by pushing it deep into the heap of grains. This temperature is given importance due to the very fact that it affects the temperature of mix and its quality directly. Also the heat transfer from coarse grains to the fine grains and powdered graphite takes place. The grain temperature depends on the following parameters:

- Combustion Chamber Temperature
- Grain Heater Drum Temperature
- Retention Time in Grain Heater

The more is the value of combustion chamber temperature, grain heater drum or retention time; the higher will be the grain temperature. The rule base formed for Grain Temperature is given in table A1of Appendix A.

(b) Mix Temperature: Mix Temperature is the temperature of the fully prepared mixture after mixing of all the grain types, graphite and dosing of liquid pitch. If the temperature is obtained as per specification then the mix can directly taken for making of the bricks in the plant press. The Mix temperature depends on following parameters:

- Grain Temperature
- Mixer temperature
- Mixing time

Higher the grain temperature, Mixer temperature and the Mixing Time, higher will be the mix temperature. The rule base formed for Mix Temperature is given in table A2 of Appendix A

(c) Press Mix Temperature: Press Mix Temperature is the Mix Temperature at the time of the mix going in for making of the bricks It happens very regularly that the Mix temperature varies from its actual required value and the mix has to be cooled down or reheated by repeating the process of heating. Cooling takes place by just leaving the drum containing mix on one side for some time and let it cool naturally. This is called Storage time Other method to cool the mix quickly is to raise the drum to certain height and pour the mix slowly into another drum on ground thus letting it dissipate heat to surrounding air. One such process is called rolling of the mix and this process can be repeated a number of times. Thus the Press Mix Temperature will depend on following parameters.

- Mix temperature
- Storage time
- Number of rolls

The Mix temperature is brought to the specified value of Press Mix temperature by storage time and the number of rolls. The rule base is shown in table A3 of Appendix A.

(d) Green Bulk Density: This is the most important property of brick in the plant process. If the green BD is achieved correctly, the other properties given the correct composition of materials and their quality will generally will be as per the specifications. Green BD will directly depend on the following parameters:

- Press Mix Temperature
- Forming pressure
- Pitch quantity
- Graphite quantity

The rule base from green BD is shown in table A4 of Appendix A

(e) Cold Crushing Strength: The CCS of bricks depends on following:

- Pitch quantity
- Green Bulk Density
- Tempering Status

The rules derived from the knowledge base are given in table A5 of Appendix A

(f) Coked Porosity: The CP of bricks depend on the following:

- Pitch quantity
- Green Bulk Density

The rules derived from the knowledge base are given in table A6 of Appendix A

(g) Hot Modulus of rupture: The HMOR depends on the following:

- Green Bulk Density
- Cold crushing strength
- Retained Carbon (RC)
- Metal powder (MP)

The rules derived from the knowledge base are given in table A7 of Appendix A

(h) Slag Corrosion Index: This is also specified in terms of Slag Corrosion Resistance. The SCR depends on the following parameters:

- Retained Carbon
- Chemical purity (CHP)
- Coked Porosity

The rules derived from the knowledge base are given in table A8 of Appendix A

(i) Oxidation Resistance: The Oxidation Resistance depends on the following parameters:

- Green Bulk Density
- Retained Carbon
- Metal powder

The rules derived from the knowledge base are given in table A9 of Appendix A.

4.3 Rule Base From Available Data

The Data available at start from plant was only 41 lines up to the Green BD stage. However further data was provided and the data totaled to 86 lines. The Data Based Rules are formed only up to the green BD stage, as the plant was not able to provide with data for parameters after GBD stage. The rules were made with the following inputs to get the green BD output:

- Combustion Chamber Temperature
- Grain Heater Drum Temperature
- Retention Time in Grain Heater
- Mixer temperature
- Mixing time
- Mix temperature
- Storage time
- Number of rolls
- Press Mix Temperature
- Forming pressure

The other parameters like the granulometry, pitch quantity and graphite quantity in the data was fixed and remained constant. Thus the same were not used as input Depending on the importance of each variable the data was allotted a symbolic value like high, very high and so on depending on the numeric value taken by it. The rules were formed on the basis of membership functions derived from a simple calculation on each attribute. This is discussed in chapter 5. The data from plant was very inconsistent and did not show any particular pattern To observe a pattern with in the data at least 2000 lines of data will be required. The system can become refined only after data to the tune of 3000 to 4000 lines is available. To solve the problem the program has been made in such a way, wherein the inputs have to be fed and if the rule does not exist then the actual Green BD as obtained is asked. Once this is done then the program automatically updates the rule base. Thus the rule base will automatically be updated as the new data becomes available The module is explained in chapter 5.

4.4 Use of ID3 Algorithm on the Rule bases

The formation of a decision tree using ID3 can be easily understood taking the following example. We consider a plant process with the rule set as given in table 4.1.

PMT	FP	PITCH	GRAPHITE	GBD
HIGH	MEDIUM	LOW	HIGH	LOW
MEDIUM	HIGH	HIGH	MEDIUM	HIGH
HIGH	LOW	HIGH	MEDIUM	HIGH
MEDIUM	LOW	HIGH	MEDIUM	MEDIUM
MEDIUM	MEDIUM	LOW	HIGH	MEDIUM
LOW	HIGH	HIGH	MEDIUM	LOW
HIGH	HIGH	HIGH	MEDIUM	MEDIUM
LOW	LOW	HIGH	MEDIUM	HIGH
LOW	MEDIUM	LOW	HIGH	LOW

Table 4.1: ID3 example

From table 4.1 and referring to equation (3.1) we have,

- Four attributes (PMT, FP, PITCH and GRAPHITE); thus K=4
- Three clauses (i.e , GBD is either high, medium or low), thus N=3
- Three values for the attribute PMT (high, medium or low); thus $M_1=3$
- Three values for the attribute FP (high, medium or low); thus $M_2=3$
- Two values for the attribute PITCH (high or low); thus $M_3=2$
- Two values for the attribute GRAPHITE (high or medium); thus $M_4=2$

We then compute the values of the entropy for each of the attributes using equation (3.1). To compute the entropy for the attribute PITCH we proceed as follows:

$p(a_{3,1}) = P$ (PITCH is high) = 6/9

$p(a_{3,2}) = P$ (PITCH is low) = 3/9

$p(c_1|a_{3,1})$ = P(GBD is high when PITCH is high) = 3/6

$p(c_2|a_{3,1})$ = P(GBD is medium when PITCH is high) = 2/6

$p(c_3|a_{3,1})$ = P(GBD is low when PITCH is high) = 1/6

$p(c_1|a_{3,2})$ = P(GBD is high when PITCH is low) = 0/3

$p(c_2|a_{3,2})$ = P(GBD is medium when PITCH is low) = 1/3

$p(c_3|a_{3,2})$ = P(GBD is low when PITCH is low) = 2/3

Substituting the values in equation (3.1) we have

$$H(GBD|PITCH) = \{(6/9) * [-3/6*\log_2(3/6) - 2/6*\log_2(2/6) - 1/6*\log_2(1/6)]\}$$

$$+ \{(3/9) * [-0/3*\log_2(0/3) - 1/3*\log_2(1/3) - 2/3*\log_2(2/3)]\}$$

$$= 1.2787$$

On similar computation we get,

H (GBD|FP) = 1.140333

H (GBD|GRAPHITE) = 1.2787

H (GBD|PMT) = 1.40333

Thus as the entropy of FP and PMT is minimum, we place FP arbitrarily as the top node. We then form three tables with FP = high, FP = medium and FP = low as given in table 4.2, 4 3 and 4 4 respectively.

PMT	PITCH	GRAPHITE	GBD
MEDIUM	HIGH	MEDIUM	HIGH
LOW	HIGH	MEDIUM	LOW
HIGH	HIGH	MEDIUM	MEDIUM

Table 4.2 (FP = high)

PMT	PITCH	GRAPHITE	GBD
HIGH	LOW	HIGH	LOW
MEDIUM	LOW	HIGH	MEDIUM
LOW	LOW	HIGH	LOW

Table 4 3 (FP = medium)

PMT	PITCH	GRAPHITE	GBD
HIGH	HIGH	MEDIUM	HIGH
MEDIUM	HIGH	MEDIUM	MEDIUM
LOW	HIGH	MEDIUM	HIGH

Table 4 4 (FP = low)

We now repeat the process of entropy calculation for the above three tables and select the node at each level with the lowest entropy. Here for the present example we see that the output or target variable gets classified after the second node itself The decision tree formed is shown in figure 4.1 Following similar lines the ID3 algorithm was applied to the rulesets given in table A1 to table A9 of Appendix A. The result of ID3 algorithm is shown for table A1 to table A9 in Figure B1 to Figure B9 of Appendix B in form of tree as obtained from program output.

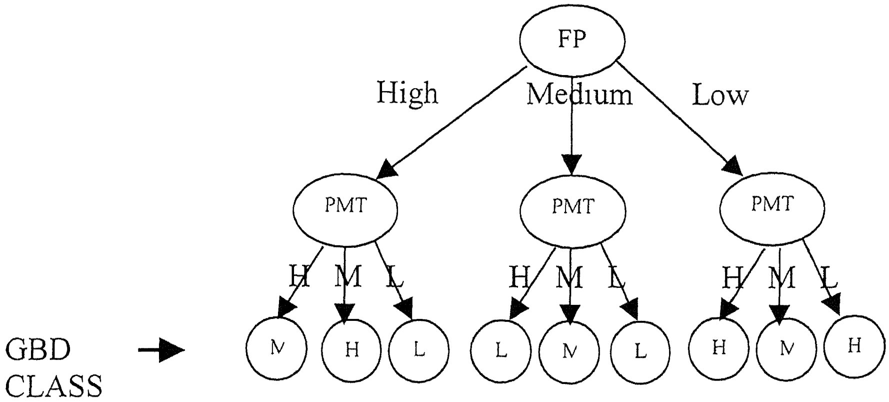

Figure 4.1: Decision Tree for GBD from ID3 Example of table 4.1

All the decision trees from rulesets given in table A1 to table A9 of Appendix A were obtained using a prolog program One such tree output is explained taking another example from rules obtained through plant data and is solved mathematically in Appendix J. The tree is also compared with the program output.

CHAPTER 5

FUZZY EXPERT SYSTEM FOR BRICK MANUFACTURING

5.1 Introduction

The expert system for the MgO-C Brick manufacturing process has been developed in two modules One of the modules as mentioned earlier is based on the knowledge acquired from the experts and the inputs from the personnel of plant. The other module has been made from the rules obtained from the data acquired from plant. Both the modules are described in detail. The modules are developed using Flex and Flint software. The Flint software is loaded when called for. As some of the things were not feasible in Flex and Flint, Prolog code was used.

5.2 Defining Fuzzy Variables and Membership Function

First the fuzzy variables and qualifiers that are going to be used in the fuzzy program are decided. We do this first by looking at the quantities that will be used by the fuzzy rules. Here for explanation we take an example of finding Grain Temperature In this case 'Combustion Chamber Temperature', 'Grain Heater Drum Temperature' and 'Retention time' are the input variables. We will define a fuzzy variable for each of these. Then we need to know what sorts of words the fuzzy rules are going to use to describe each fuzzy variable. These words become the linguistic qualifiers of the fuzzy variable. Let's look at the 'Combustion Chamber Temperature' fuzzy variable The definition of a fuzzy variable may also include a definition of the range of 'crisp' values it may take The range of Combustion chamber temperature possible for the plant may broadly be defined as being between 0 and 800 degrees Celsius, though the significant values lie between 300 and 400. Thus the range of 'Combustion Chamber Temperature' may vary from 0 to 800 and is not expected to go beyond. The range is selected carefully. Any input the operator selects out of this range (say 805) the programme will not accept the same.

The temperature of the combustion chamber is normally described using the adjectives like high, medium and low. We need to define a qualifier for each of these

fuzzy variables. The easiest way to implement any qualifier is to define it using a linear shape so that the lines between the points are always straight and not curved Refinements to the membership function can be introduced, if needed, at a later stage after comparing of program results with the actual results. As is obvious 'low' qualifier in our example should refer to temperatures at the lower end of the fuzzy variable and this means it will use the downward slope shape. By talking to the plant experts it was decided that the 'low' qualifier would definitely refer to all the values below 300 and possibly to the values below 350 and not to the values above 350. The values between 300 and 350 should become steadily less 'low' in a linear fashion. In similar fashion the qualifiers for medium and high temperatures were decided. This thus forms the membership function for the fuzzy variable 'Combustion Chamber Temperature'. The construction of membership function using linear and curved membership is shown in figure 5.1.

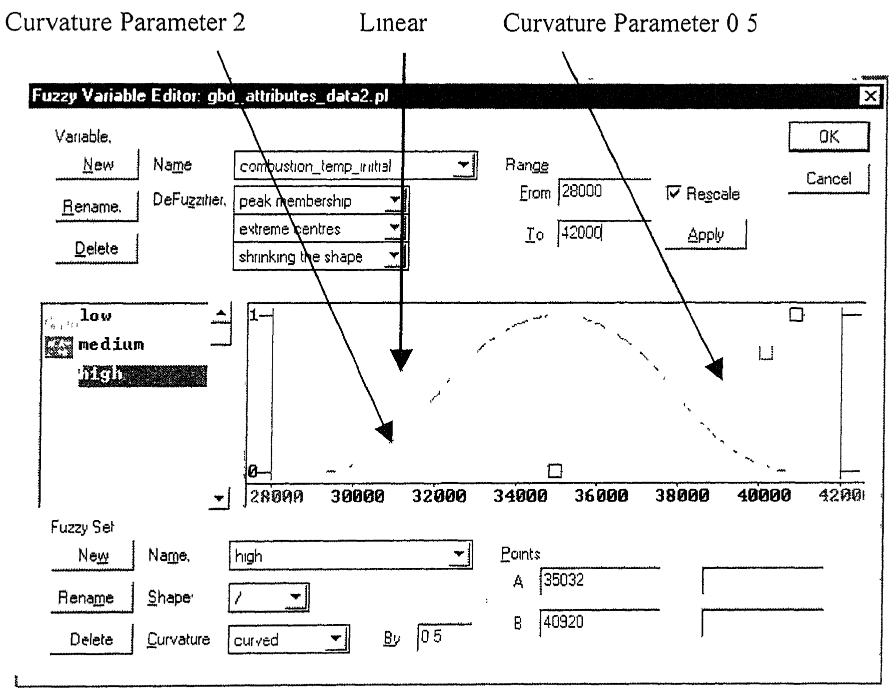

Figure 5.1 Membership function Construction

The other input fuzzy variables and also the output variable are defined in a similar way. The membership functions can be defined in the program itself or a separate file can be made and called from the program

5.3 Defining Fuzzy Rules

After defining the fuzzy variables for the problem we then proceed to the fuzzy rules Their are many rules relating to combustion chamber temperature, grain heater drum temperature and retention time that have been obtained after talking to the experts. In this case the rules will cover all the possible combinations as shown in table A1 of Appendix A. Three rules, from the experts, are written below:

- *'if the combustion chamber temperature is high and the grain heater drum temperature is high and the retention time is high then the resulting grain temperature is bound to be very high'* .
- *'if the combustion chamber temperature is high and the grain heater drum temperature is low and the retention time is medium then the resulting grain temperature is low'*
- *'if the combustion chamber temperature is low and the grain heater drum temperature is high and the retention time is average then the resulting grain temperature is medium'*

5.3.1 Format for storing rules

Once the rules are made the ID3 program is run on the rules. The format for the rules given in table A1 of Appendix A for running the ID3 program is specified in table B1 of Appendix B. Here we define the classes of output variable (here very_high, high, medium, low and very_low). Also the input attributes have to be specified (here cti, ghdt and rt) This format is stored as '.pl' or '.txt' file. Once the ID3 program is run we will get resulting output as a decision tree as shown in figure B1. Then we can proceed writing the rules in Flex in the following manner.

rule grain_temp_rule_1

if the ghdt is high

and the rt is high

and [the cti is high or the cti is medium]

then the gt becomes very_high

Alternatively, because the rules always apply to the same input variables, we can combine them all into a single fuzzy matrix. The fuzzy matrix format for the table A1 is specified in table B2. This matrix is to be stored as '.pl' file and is called from within the Flex program.

5.4 The Structure of a Fuzzy Logic Program

Once the input and the output attributes are decided, the membership functions are defined and the rules have been stated then the fuzzy program can be made in a way to accept the input in the form it is available The input can be taken from a file or can be entered by the operator as per program design A fuzzy logic program can be viewed as a three stage process:

- Stage 1 - Fuzzification, the 'crisp' input values are assigned to the appropriate input fuzzy variables. The 'crisp' input value is converted into a degree of membership for each of the qualifiers for the fuzzy variable it is assigned to.
- Stage 2 - Propagation, fuzzy rules are applied to the fuzzy variables and their qualifiers When a fuzzy rule is applied to some fuzzy variables the degrees of membership for the qualifiers mentioned in the conditions of the rule are propagated to the qualifiers mentioned in the conclusions of the rule.
- Stage 3 - De-fuzzification, the resultant degrees of membership for the qualifiers of the output fuzzy variables are converted back into 'crisp' values.

5.5 Module-1: Program Based on Rules from Expert Advice

In this module the program was made on the basis of the knowledge gathered from experts, plant personnel and the flowchart handed over by RDCIS as shown in figure 5.2. The membership functions for this module were formed for all the attributes as explained in paragraph 5.2 and are shown in Appendix C In figure 5.2 we see that the inputs

Combustion Chamber Temperature, Grain Heater Drum Temperature and Retention Time result in the output Grain Temperature. Similarly the Grain Temperature, Mixer temperature and Mixing time result in the output Mix Temperature and so on. Thus the program was made in a modular form taking inputs, getting an output and then converting the output of the current stage as input to the next stage along with the other new inputs. For example to find Cold Crushing Strength the inputs that will be asked from the operator will be Green BD, Pitch Quantity and Tempering Status However if the operator wants to find CCS from the start of plant process then he will be required to feed in all the requisite parameters for GBD and the GBD will not be asked as it is being computed from previous inputs.

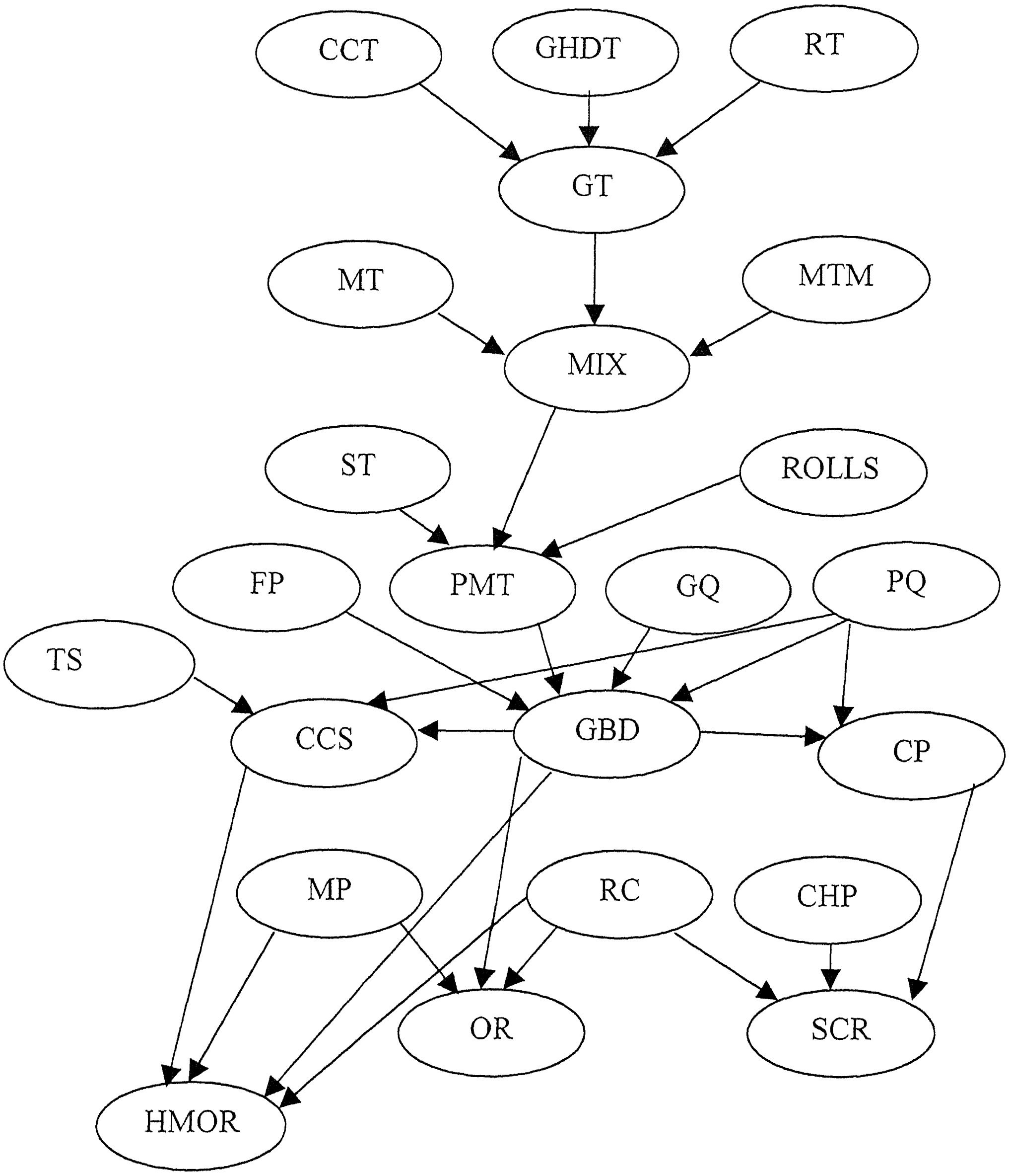

Figure 5.2: Dependence of Parameters and Properties for Brick Manufacturing

CCT. Combustion Chamber Temperature
GHDT Grain Heater Drum Temperature
RT. Retention Time
GT Grain Temperature
MT· Mixer Temperature
MTM· Mixing Time
MIX. Mix Temperature
HMOR High Modulus Of Rupture
PMT· Press Mix Temperature
FP. Forming Pressure
PQ Pitch Quantity
GQ Graphite Quantity
GBD: Green Bulk Density
ROLLS Number Of Rolls
CCS Cold Crushing Strength
SCR· Slag Corrosion Resistance
CP Coked Porosity
MP. Metal(Al) Powder
ST Storage Time
OR Oxidation Resistance
TS Tempering Status
CHP Chemical Purity
RC· Retained Carbon

5.5.1 Sub Modules

The module is divided into sub-modules and we can choose any of the properties or parameters relating to plant process. On running the program a question will be asked as depicted in figure 5.3

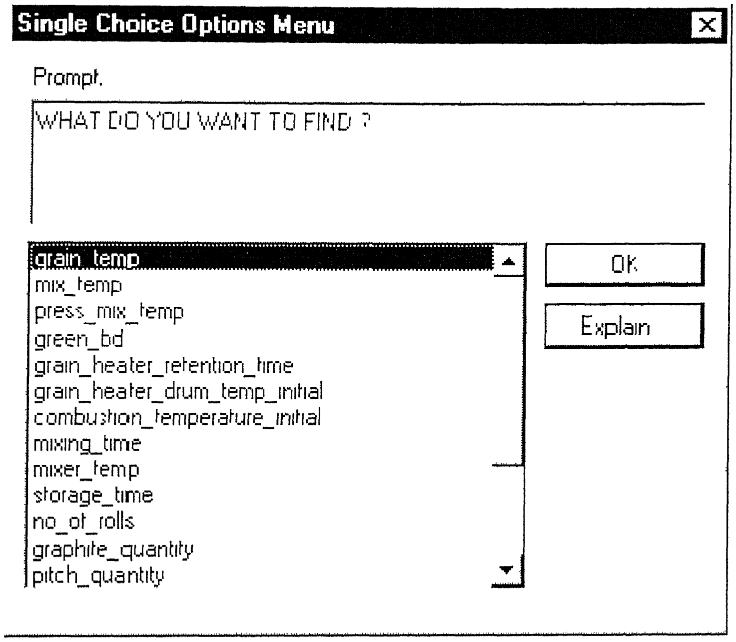

Figure 5 3 Sample Question of program

The working of program can be easily understood with the help of flowchart given in figure 5.4. Suppose Grain Temperature is chosen. Then a question will be asked to use either forward chaining (inputs: CCT, GHDT and RT) or backward chaining. In backward chaining there are again two possibilities. One is with less inputs (Mixer Temp, Mixing Time and Mix Temp) and other with inputs that start backwards from GBD to Mixer Temperature. The program then asks the input in crisp form. Once all inputs are available then program calls the membership functions and assigns to these inputs the corresponding degree of membership to the qualifiers as per the value taken by them. After this the fuzzy rules (matrix) are called and all the rules are checked for firing. The number of rules then fired is propagated to the qualifiers mentioned in the conclusions of the rule. After this in de-fuzzification process, the resultant degrees of membership for the qualifiers of the GT fuzzy variable is converted back into 'crisp' values. This is

explained in examples to follow. The process of Module-1 is explained in detail in Appendix K. Also the fuzzification and de-fuzzification process is explained pictorially.

5.5.1.1 Example-1

Inputs are CCT = 400 (High with membership 1)

GHDT = 400 (Medium with membership 1)

RT = 4 (Low with membership 1)

Rule fired is: If CCT is High and GHDT is Medium and RT is LOW then GT is Medium.

Result will be de-fuzzified to Medium with a membership function of 1 and thus the output will be180.

5.5.1.2 Example-2

Inputs are: CCT = 400 (High with membership 1)

GHDT = 400 (Medium with membership 1)

GT = 180 (Medium with membership 1)

Rules fired If CCT is High and GHDT is Medium and GT is Medium then RT is Medium.

If CCT is High and GHDT is Medium and GT is Medium then RT is Low.

Result will be de-fuzzified to Medium with a membership function of 1 from the first rule fired and will result in output 5. Also similarly from the second rule fired we get the output 4. Thus the result will be the centroid of both the output values giving the output of 4.5.

5.5.2 Results of Module-1

The results of module-1 corresponding to rules in table A1 to A9 are given in table D1 to table D9 in Appendix D

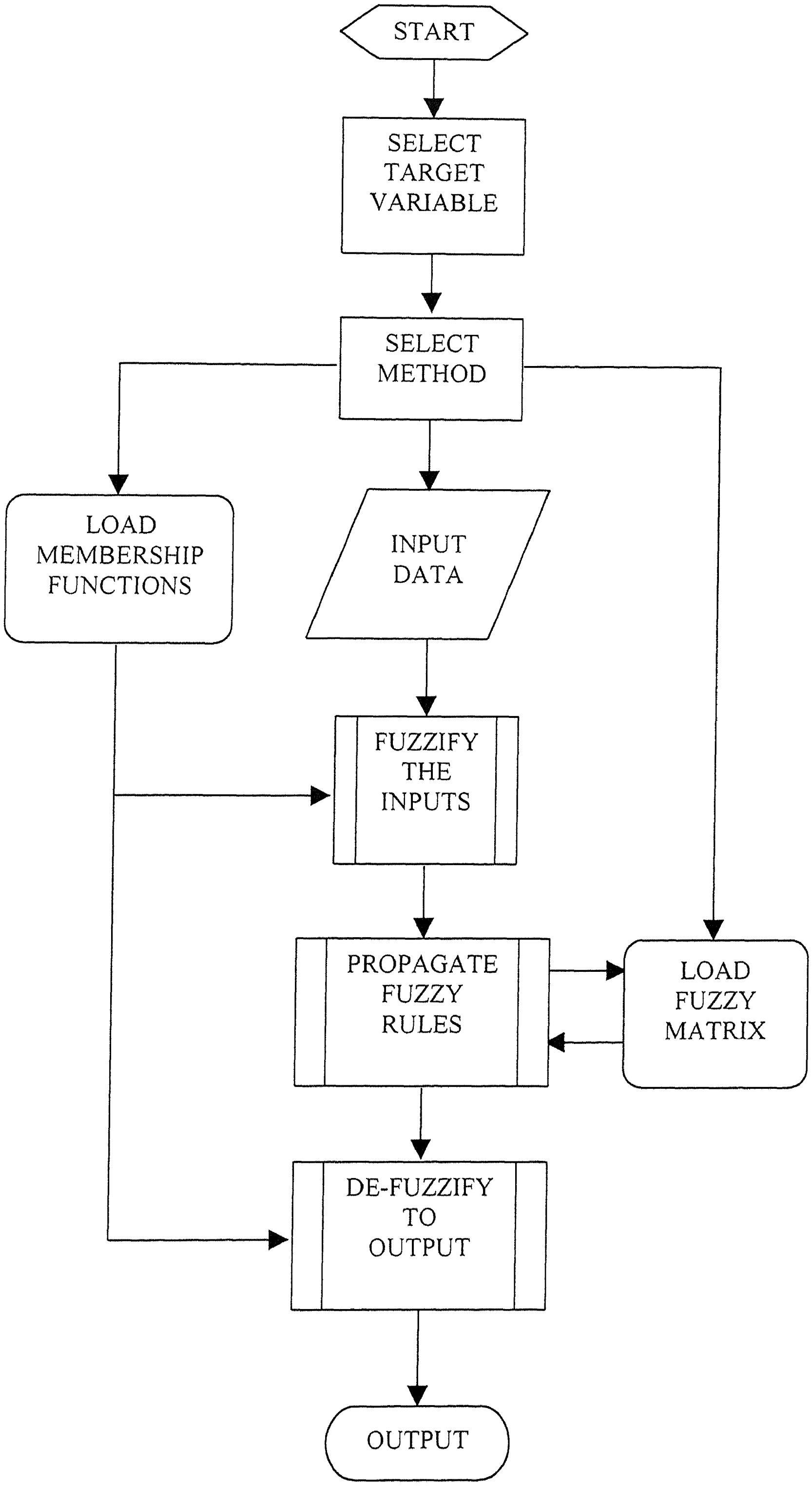

Figure 5.4: Flowchart for Module-1

5.6 Module-2: Program Based on Rules from Plant Data

This module is made based on the data provided by SAIL The data provided was consisting of 86 records and is given in table E1 of Appendix E The module is developed only up to the Green Bulk Density stage, as the data for further properties and parameters was not available The main aim of this expert system was to get the GBD within the specified limits as once this is achieved all the other properties of bricks generally fall in the acceptable limits The module discussed here is developed using the 10 inputs mentioned in paragraph 4.3 and resulting in the output GBD The parameters like Granulometry, Pitch Quantity and Graphite Quantity were not included in the present model as these quantities were fixed However a module inclusive of these parameters was developed and handed over to the plant From the data available it can be seen that the data is inconsistent and a pattern does not exists with only these many records. Because of shortage of data it was not possible to capture all the rules. Also the plant processes being complicated there are bound to be variations in all the parameters to a great extent. To overcome this problem the program was developed in such a way that it will result in the output if at least one rule fires otherwise it updates the ruleset as will be explained later.

5.6.1 Membership Functions

The membership functions were formed conforming to the data. For each of the attributes in table E1, the mean and the standard deviation was calculated. Then as per the importance of each attribute towards the end result the number of fuzzy qualifiers were decided. The creation of membership function is explained taking the example of input attribute Press Mix Temperature From the PMT column of table E1 we get a mean of 122.88 and a standard deviation of 6.67. Using 5 qualifiers the membership function was constructed as shown in figure 5.5

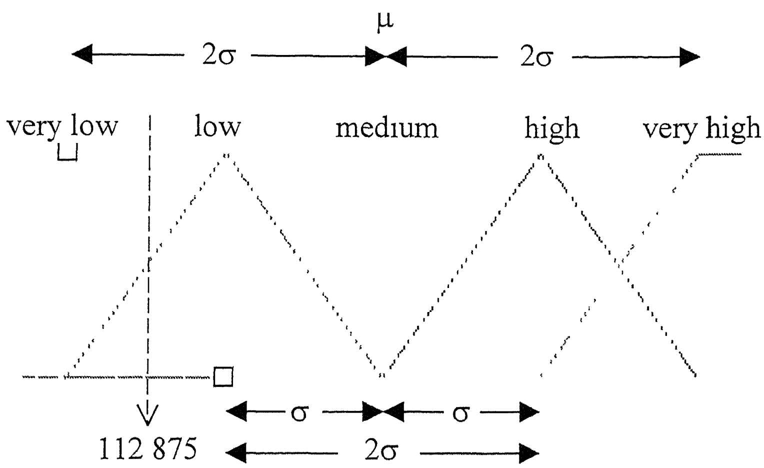

Figure 5.5 Construction of Membership Function for Module-2

The membership functions for all the attributes created from the data likewise are shown in Figure F1 to Figure F11 in Appendix F

5.6.2 Rule Base

The rule base for the module was made by considering each of the value every attribute took and converting that value to the respective qualifier. This was done through a program that receives the numerical inputs and converts them to high, low or otherwise as per the respective attributes. Considering the example of PMT as given in paragraph 5.6.1, when the input will lie between 119.545 to126.215 the qualifier will take the value 'medium'. Similarly if the input is below 112.875 the qualifier becomes 'very low'. This is shown in figure 5.5. The rules so made are given in table E2 of Appendix E. Also the rules obtained after running the ID3 program are given in table E3.

5.6.3 Program for Module-2

The program after accepting the numerical inputs calls another routine to convert the attribute values to qualifiers. Once the qualifiers are allotted, they are stored in a fixed format in a temporary file Then the rule stored is compared with all the previously existing rules stored in a separate file. The moment the first match is found, another program is called and the frequency of firing of that rule is updated for displaying with the result After this from the main program the membership functions and fuzzy matrix are called Then the process of fuzzification, rule propagation and de-fuzzification as described for module-1 takes place and the result is obtained. In case the comparison of rule fails than the operator is told that the rule for the current inputs does not exists and is given a choice for updating the rule. In case rule has to be updated than the actual Green Bulk Density obtained from the plant process has to be specified. This value is converted to the corresponding qualifier and then the rule is stored in the fuzzy matrix. Here onwards for any inputs falling within the scope of this newly constructed rule the program will result in output The above process is shown as flowchart in figure 5.6.

As mentioned earlier this was done due to shortage of data The plant provided further data and when this data was fed to the system, the program updated the rules. After the rules start showing some pattern (frequency of rule firing is stored), the ID3 algorithm can be run on the rules and a minimum set of rules can be obtained

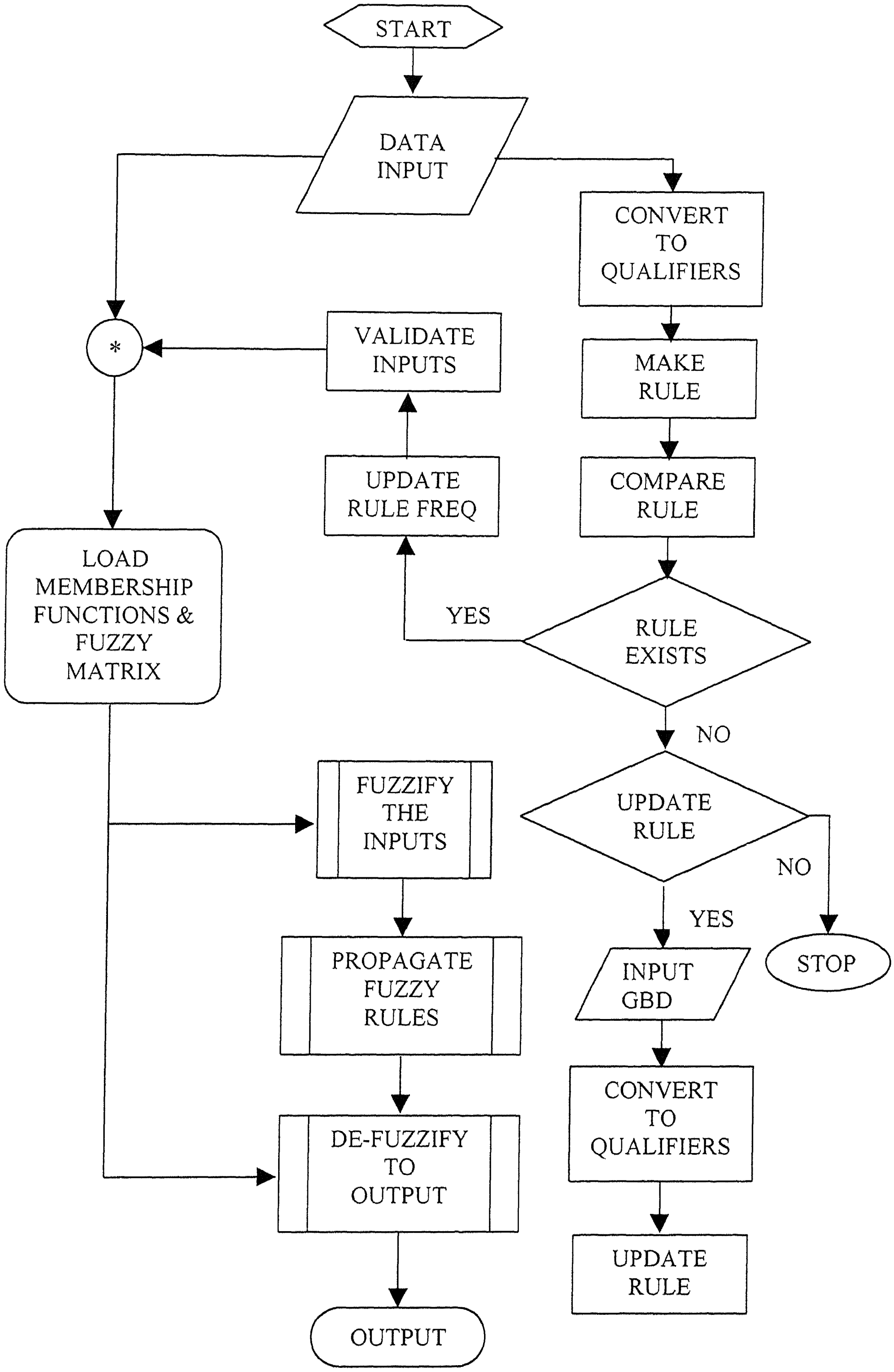

Figure 5.6: Flowchart for Module-2

5.6.4 Results of Module-2

The Green Bulk Density output for the plant data given in Table E1 of Appendix E is given in table G1 of Appendix G The deviation from the GBD obtained at plant is also shown. The maximum and minimum deviations obtained from desired value using centroid de-fuzzification were 0.0477 and 5^{-6}, whereas using peak method were 0.0292 and 0 0003 respectively. The average deviation obtained was 0 36 % for centroid method and 0.34 % using peak method.

5.7 Comparison of Results

The results for Green Bulk Density from module-1, module-2 and that obtained using Fuzzy Logic Toolbox of Matlab using centroid de-fuzzification were compared and are discussed below

5.7.1 Comparison of results of Module-2 with different curve parameters

GBD from plant data was compared after introducing change in shape of membership functions of module-2 by assigning curvature parameters of 0.1, 0.5, 2 and 6 to all the attributes. The results obtained are shown in table G2 of appendix G. As per expectations it is seen that many of the results have remained unchanged owing to the fact that the rules have fired with a fixed value of membership being taken. The results have changed slightly where the de-fuzzified value of GBD falls on the curves. As can be seen as the membership changes from linear to curvature parameter of 2 and 6 the value of GBD increases slightly. Thus once the system is stabilized the shape of membership functions can be altered as per the desired results.

5.7.2 Comparison of results of Module-1 and Module-2 using plant data

The plant data was fed to module-1 to obtain the mix temperature, press mix temperature and the Green BD. The inputs for obtaining Mix temperature were Combustion Chamber Temperature, Grain Heater Drum Temperature, Retention Time, Mixer Temperature and Mixing Time. Similarly for obtaining Press Mix Temperature the Mix Temperature so obtained, Storage Time and Rolls done were used. For obtaining GBD the Pitch quantity and Graphite quantity was kept fixed at 4.4% and 5%

respectively and Forming Pressure was fed from plant data. As is seen from the table G3 there is a large variation in Mix Temperature and Press Mix Temperature from the available data. The variation in Mix temperature itself has propagated further. However the Green BD obtained was very close to the desired value. This was due to the reason that the rules have been made in such a way that the GBD will be obtained to near perfection if the Graphite and Pitch Quantities are kept fixed This was observed using Bayesian Networks and is discussed in Chapter 6.

5.7.3 Comparison of results with Fuzzy Toolbox of Matlab using Plant Data

The results were compared on the plant data given in table E1 As the numbers of inputs were 10 and each of the attributes took qualifiers like high, medium and so on, the total numbers of rules possible are 3^9*5 (= 15000000000). As only 86 records were available, each of these records formed a distinct rule. Due to this reason, the program in Matlab had to be trained and tested on the same data set. The result of Module-2 and Matlab [11] for resulting GBD is compared in Table G4. As is seen from the table, the average deviation from the desired value of GBD of table E1 from Module-2 and Matlab is 0.00318977 and 0.004772326 respectively. Thus we see here that the output of both the systems is quite satisfying.

5.7.4 Comparison of results with Fuzzy Toolbox of Matlab using Fabricated Data

A data set was made in such a way that it would not change the rules given in table E2 of Appendix E. Thus the data was tailor-made for the existing rules for module-2. The changes in the data were varied as much as possible from plant data without disturbing the qualifier values. The Matlab program was trained on the plant data and tested on this data The data along with the results of Module-2 and Fuzzy Logic Toolbox of Matlab is given in table G5. The maximum, minimum and average GBD obtained from model-2 is 3.1797, 3.0349 and 3.1 that is quite realistic. Where as, for Matlab Fuzzy Toolbox, the values are 5.4399, -1.679566 and 2.7981 respectively. As the rules exist in Module-2 for the data, we see that the resulting GBD is quite close to the results of plant data. Thus we see that if the rule exists, then the Flint system gives realistic results. We see from table

G5 that the Matlab results for this case are totally vague, as the rules formed by the training set of Matlab do not support this data.

5.8 FLINT system compared with Matlab Fuzzy Logic Toolbox

As seen from the discussions on results above, the FLINT system will give realistic results when a rule exists. When the rule does not exist result is not produced This is not the case with Matlab as it always gives the result. However if sufficient data is not available for training, Matlab results are not all that encouraging. The Matlab toolbox has got advantage over the FLINT system, that the rule base, as well as membership functions are created by the system itself from the input data and with more data to train on, the system will become refined on its own. For the FLINT system the rules have to be made and written into the program. For both the systems to work efficiently the data available for making rules or training should be such that almost all the rules are captured. One other major advantage of FLINT system over Matlab Toolbox is that it is very fast and gives the result immediately

CHAPTER 6

USE OF BAYESIAN NETWORKS AND MULTIVARIATE ADAPTIVE REGRESSION SPLINES

6.1 Introduction

This chapter discusses the results obtained from Microsoft Bayesian Networks and Multivariate Adaptive regression splines. These tools were used for the validation of rules, checking the relationship between the variables, assessing probabilities of various attributes, effect of an attribute on the other attributes and the importance given to each of the variable.

6.2 Microsoft Bayesian Networks (MSBNX)

MSBNX [10] is a Microsoft Windows software application that supports the creation, manipulation and evaluation of Bayesian probability models. Each MSBNX model is represented as a graph or diagram. The random variables are shown as ellipses, called nodes, and the conditional dependencies are shown as arrows between variables. MSBNX only supports discrete distributions for its model variables.

6.2.1 Belief Network

A belief network is commonly represented as a graph, which is a set of nodes and arcs. The nodes represent the variables and arcs represent the conditional dependencies in the model. A variable is an element of a probability model that can take on a set of different values that are mutually exclusive and exhaustive. The absence of an arc between two variables indicates conditional independence such that there are no situations in which the probabilities of one of the variables depend directly upon the state of the other. In construction of a belief network we have to include all variables that are important in the model, use causal knowledge for the connections made in the graph and also use a priori knowledge to specify the conditional distributions. Causal knowledge in means linking variables in the model in such a way that arcs lead from causes to effects. In probability theory, there is no a priori way of knowing which variables influence other

variables. Here the complete or joint probability distribution must be known to correctly perform inference

6.2.2 Inference

Inference or model evaluation is the process of updating probabilities of outcomes based upon the relationships in the model and the evidence known about the situation at hand. In a Bayesian model, the evidence about recent events or observations is applied to the model by "instantiating" or "clamping" a variable to a state that is consistent with the observation. Then the probabilities of all the other variables that are connected to the variable representing the new evidence are updated. These updated probabilities reflect the new levels of belief in (or probabilities of) all possible outcomes coded in the model.

6.2.3 Prior Probability Distributions Supported by MSBNX

- **Discrete Sparse.** This is the standard type of distribution. All possible probabilities are available, but there is no requirement that all values be specified During evaluation, uniform distributions are automatically supplied for unassessed probabilities.
- **Causally Independent.** This type of distribution compresses the space of necessary probabilities by assuming that certain states of the parent nodes are mutually exclusive.

6.2.4 Methods of Probability Assessment Used by MSBNX

- Standard assessment is a table-based method. In this we locate and edit a particular set of probabilities based upon the states of the parents of the variable.
- Causally Independent: is a type of standard discrete assessment. It uses a special type of distribution based upon assumptions about conditional independence among the parents of a variable.
- Asymmetric assessment: is a tree-based method. In this we create sets of probabilities, organized as a decision tree, by making explicit distinctions between states of parents of the variable.

6.2.5 Creation of Belief Network for Module-1

The belief network created for the Green Bulk Density stage is shown in figure 6.1 The network was created with following steps.

- For each attribute the qualifiers as given in Appendix A were defined
- The causal dependency relationships between the variables were than established. This involves creating arcs (lines with arrowheads) leading from the parent variable to the child variable.
- Then the prior probabilities were assigned to each variable. This means supplying the model with numeric probabilities for each variable in light of the number of parents the variable was given.

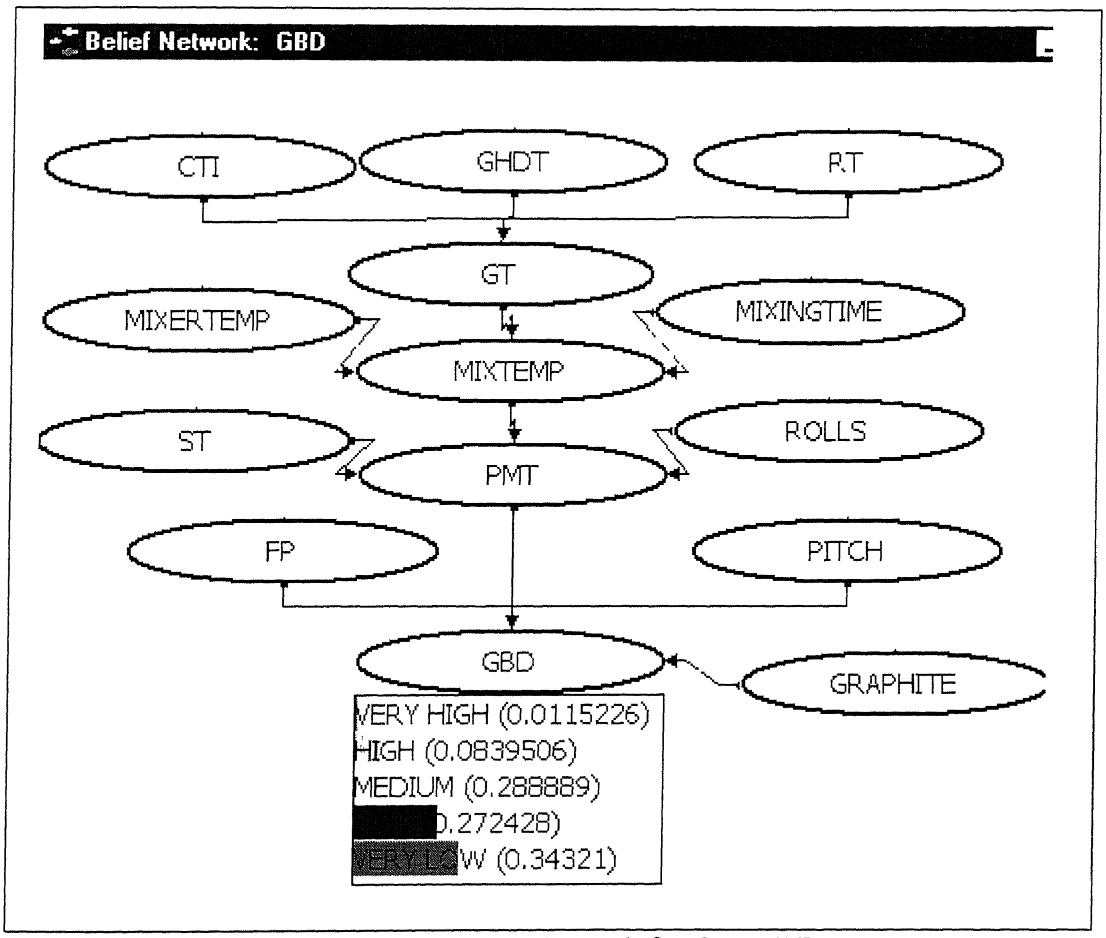

Figure 6.1 MSBNX Network for Green BD

6.2.6 Results and Inference from the Network

Each of the nodes can be selected separately or in conjunction with other nodes and the probability changes for all the other selected nodes can be monitored either on the network itself or with the other features like Bar Charts or on the spreadsheet as tables. A few results after assigning the states are shown in tables of Appendix H. Considering CCT=High and no evidence selected for other variables. We see from table H2 that the probability of GBD being medium is Highest and that of being low or very low comes next Similarly the effect on all the attributes can be viewed Now if we make GHDT=Medium than we see from table H6 that the probability of GBD being very low is highest and so on Thus the contribution of every input either singly or with combination with other attributes can be studied. This network can also be used for validation of rules. As seen from tables H20 and H21 the rules are.

- IF Pitch is Medium and Graphite is Medium and PMT is low THEN the GBD is Low.
- IF Pitch is Medium and Graphite is Medium and PMT is High THEN the GBD is Medium

Thus we see here that Forming Pressure has got no role to play, which should not be the case. A low forming pressure will imply a very low Green BD. Similarly all the rules can be constructed and validated using this network. It is because of this reason that the GBD obtained from module-1 is giving very good results even when the Mix Temperature and Press Mix Temperature are deviating to a great extent. Thus we now know that the rule bases with these inputs need to be changed. The network can also be used to refine the shapes of membership function. Consider for example that Grain Temperature on CCT being high, GHDT being Medium and RT being Medium is Medium with probability 0.337 and Low with probability 0.336. However if the knowledge gathered from expert is that there are more chances of getting GT as medium than we can change the curvature parameter of membership function accordingly after studying the effect of the same on other rules.

6.3 Data Analysis Using MARS

To check the relationship between different variables and their relative importance the MARS software was run on the plant data. MARS produces simple graphs displaying the relationship between each important variable and the target

6.3.1 MARS Splines and Knots Selection

The two types of curve fitting generally used are interpolating splines (a spline passes through every data point) and smoothing splines (the curve needs to be close to the data points). Mars uses piece-wise linear regression splines. Instead of fitting a single straight line to the data, the regression is allowed to bend. A key concept underlying the spline is the knot. A knot marks the end of one region of data and the beginning of another Thus, the knot is where the behavior of the function changes. Between knots, the model could be global (e.g , linear regression). In a classical spline, the knots are predetermined and evenly spaced, whereas in MARS, the knots are determined by a search procedure. Only as many knots as needed are included in a MARS model. If a straight line is a good fit, there will be no interior knots.

6.3.2 Basis Functions

In MARS, basis functions are the machinery used for generalizing the search for knots. Basis functions are a set of functions used to represent the information contained in one or more variables. Much like principal components, basis functions essentially re-express the relationship of the predictor variables with the target variable. MARS generates basis functions by searching in a stepwise manner. It starts with just a constant in the model and then begins the search for a variable-knot combination that improves the model the most.

6.3.3 Mars Model

The optimal MARS model is selected in a two-stage process. In the first stage, MARS constructs an overly large model by adding basis functions. Basis functions represent either single variable transformations or multivariable interaction terms. As

basis functions are added, the model becomes more flexible and more complex, and the process continues until a user-specified maximum number of basis functions are reached. In the second stage, basis functions are deleted in order of least contribution to the model until an optimal model is found. MARS models can be shaped and refined using the following techniques, each of which can influence the final model:

- Changing the number of basis functions generated in the forward stage
- Forcing variables into the model
- Forbidding transformation of selected variables
- Placing a penalty on the number of distinct variables (in addition to the number of basis functions)
- Specifying a minimum distance (or minimum span) between knots
- Allowing select interactions only
- Modifying MARS search intensity
- Manually selecting a model other than the optimal model from the selector

MARS accepts the input in tabular form. The data table is set for input and the target variable with the options given above have to be specified. After this the Model is created and results are displayed.

6.3.4 Results and Inference

Plant Data with 128 records was fed as input. The target variable was kept as Green Bulk Density. The maximum basis functions, the number of interactions allowed and other parameters like minimum observations between knots were changed but the results of most of the models remained identical as the number of records were less. The result of model with 12 basis functions and allowing two interactions between basis functions constructed from input variables is shown as Appendix G.

- Learning Sample statistics: This gives the mean, standard deviation, number of records read and the sum total of column.
- Ordinal response: This gives the minimum and the maximum of each attribute as well as the Q25, Q50 and Q75 points. The Q50 point means the data is centered in the region of 3 11 for GBD and around 33 for ST and so on. Q25 point means the

lower side of data is centered in the region of the value given. Thus we can use these points to develop the membership functions.

- Forward Stepwise Knot Placement This displays the basis functions in the order in which they are entered in the model. The basis functions are added until the maximum of basis functions allowed is reached. After this the basis functions are eliminated in a stepwise manner to obtain the final model. As we can see the subject table represents the basis functions for the variables and also specifies the knots representing a change of curve at that point. This is also seen in the curves and surfaces generated by the model.
- ANOVA Decomposition the first two columns in the ANOVA table list the basis function collection number and the standard deviation of the collection The larger is the standard deviation, the greater will be the contribution to the overall explanatory power of the model. The third displays the contribution of the collection of basis functions as measured by the resulting loss of fit if that entire collection were to be deleted from the model. The next two columns list that only one basis function was used for each and the number of effective parameters The final column lists that the MTM is not interacting while there is interaction between RT and ST, MT and CCT.
- Relative Variable Importance: The model variables are ranked from most to least important and displayed in the variable importance table. As is seen the maximum importance is attached to variable RT and the importance is given then to MTM, ST, MT and CCS in that order.
- Curves and Surfaces: The curve for MTM and surfaces generated by the model between RT and ST, MT and CCT are shown.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusion

The expert system for MgO-C brick manufacturing process was developed for providing with help in prediction of various parameters and assisting in controlling of process parameters. Out of the two modules developed, Module-1 was developed as per the requirements of RDCIS and is totally based on the advice of experts. Though the results obtained from this module are quite convincing, there exists certain flaws in the rule base as brought out in the discussion on results. Module-2, developed on plant data is a more realistic approach and is giving encouraging results For refining of the final output, change in shape of membership functions can be introduced as per requirement For improving the lining life of converter a rule base is required where all the rules are captured. This is possible when an adequate amount of data is made available from plant. Module-2 updates the rule base when the rule does not exist and also gives the frequency with which a particular rule is fired. Once majority of the rules are captured the ID3 algorithm can be put to use and the rule base can be minimized. The results using Matlab Fuzzy Logic Toolbox were quite satisfying when training and testing was done on the same data. However as in case of Module-2, more data is required for training to test on other data. The major advantage of FLINT system over Matlab Toolbox is that it is very fast and gives the result immediately. The Matlab toolbox has got advantage over the FLINT system, that the rule base, as well as membership functions are created by the system itself from the input data and with more data to train on, the system will become refined on its own Bayesian networks and tools like MARS can be used to validate rules, as help to construct and shape the membership functions, finding the importance and effect of each of variable with respect to other, finding effect of individual or a combination of variables on the output besides checking the authenticity of rules.

7.2 Recommendations for Future Work

The Refractory Brick Manufacturing is a complex process with many parameters and properties playing a role in the lining life of converters. To develop a foolproof system, a lot of work can go in developing of expert system The following points are listed below:

- RDCIS and RSP should be requested to provide more plant data without which, capturing of all the rules is not possible. Once all the rules are captured and incorporated in system, the results from Module-2 can be used for validation at plant.
- Module-1 needs some refinements in the rule base The same should be discussed with the experts. Alternately, membership functions for module-1 can be changed as per the rules and memberships of Module-2 after discussing with experts Presently the rule base for backward chaining was picked up from the rules of forward chaining. This gave erratic results and thus was not discussed in the work. The rule base for backward chaining should be made separately for each of the attributes.
- Once most of the rules have been captured, ID3 Algorithm can be used after which the rules be re-written in Flex, as the memory requirement for rules will reduce.
- The data from plant is provided at present only up to the Green Bulk Density stage. The plant should be requested to provide data for the parameters and resulting properties after GBD stage so that Module-2 can be further extended.

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RULE BASE FROM EXPERT ADVICE

COMBUSTION CHAMBER TEMP (CCT)	GRAIN HEATER DRUM TEMP (GHDT)	RETENTION TIME (RT)	GRAIN TEMP (GT)
HIGH	HIGH	HIGH	VERY HIGH
HIGH	HIGH	MEDIUM	HIGH
HIGH	HIGH	LOW	MEDIUM
HIGH	MEDIUM	HIGH	HIGH
HIGH	MEDIUM	MEDIUM	MEDIUM
HIGH	MEDIUM	LOW	MEDIUM
HIGH	LOW	HIGH	MEDIUM
HIGH	LOW	MEDIUM	LOW
HIGH	LOW	LOW	VERY LOW
MEDIUM	HIGH	HIGH	VERY HIGH
MEDIUM	HIGH	MEDIUM	HIGH
MEDIUM	HIGH	LOW	MEDIUM
MEDIUM	MEDIUM	HIGH	HIGH
MEDIUM	MEDIUM	MEDIUM	MEDIUM
MEDIUM	MEDIUM	LOW	LOW
MEDIUM	LOW	HIGH	MEDIUM
MEDIUM	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	VERY LOW
LOW	HIGH	HIGH	HIGH
LOW	HIGH	MEDIUM	MEDIUM
LOW	HIGH	LOW	LOW
LOW	MEDIUM	HIGH	MEDIUM
LOW	MEDIUM	MEDIUM	MEDIUM
LOW	MEDIUM	LOW	LOW
LOW	LOW	HIGH	LOW
LOW	LOW	MEDIUM	VERY LOW
LOW	LOW	LOW	VERY LOW

Table A1: Rules for Grain Temperature from Expert Advice

GRAIN TEMP (GT)	MIXER TEMP (MT)	MIXING TIME (MTM)	MIX TEMP (MIX)
VERY HIGH	HIGH	HIGH	VERY HIGH
VERY HIGH	HIGH	MEDIUM	VERY HIGH
VERY HIGH	HIGH	LOW	VERY HIGH
VERY HIGH	MEDIUM	HIGH	VERY HIGH
VERY HIGH	MEDIUM	MEDIUM	VERY HIGH
VERY HIGH	MEDIUM	LOW	VERY HIGH
VERY HIGH	LOW	HIGH	VERY HIGH
VERY HIGH	LOW	MEDIUM	VERY HIGH
VERY HIGH	LOW	LOW	VERY HIGH
HIGH	HIGH	HIGH	HIGH
HIGH	HIGH	MEDIUM	HIGH
HIGH	HIGH	LOW	HIGH
HIGH	MEDIUM	HIGH	HIGH
HIGH	MEDIUM	MEDIUM	HIGH
HIGH	MEDIUM	LOW	HIGH
HIGH	LOW	HIGH	HIGH
HIGH	LOW	MEDIUM	HIGH
HIGH	LOW	LOW	MEDIUM
MEDIUM	HIGH	HIGH	MEDIUM
MEDIUM	HIGH	MEDIUM	MEDIUM
MEDIUM	HIGH	LOW	MEDIUM
MEDIUM	MEDIUM	HIGH	MEDIUM
MEDIUM	MEDIUM	MEDIUM	MEDIUM
MEDIUM	MEDIUM	LOW	MEDIUM
MEDIUM	LOW	HIGH	LOW
MEDIUM	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	MEDIUM
LOW	HIGH	HIGH	MEDIUM
LOW	HIGH	MEDIUM	LOW
LOW	HIGH	LOW	LOW
LOW	MEDIUM	HIGH	LOW
LOW	MEDIUM	MEDIUM	LOW
LOW	MEDIUM	LOW	LOW
LOW	LOW	HIGH	LOW
LOW	LOW	MEDIUM	LOW
LOW	LOW	LOW	LOW
VERY LOW	HIGH	HIGH	LOW
VERY LOW	HIGH	MEDIUM	LOW
VERY LOW	HIGH	LOW	VERY LOW
VERY LOW	MEDIUM	HIGH	LOW
VERY LOW	MEDIUM	MEDIUM	LOW
VERY LOW	MEDIUM	LOW	VERY LOW
VERY LOW	LOW	HIGH	VERY LOW
VERY LOW	LOW	MEDIUM	VERY LOW
VERY LOW	LOW	LOW	VERY LOW

Table A2: Rules for Mix Temperature from Expert Advice

MIX TEMP (MIX)	STORAGE TIME (ST)	NO. OF ROLLS (ROLLS)	PRESS MIX TEMP (PMT)
VERY HIGH	HIGH	HIGH	LOW
VERY HIGH	HIGH	MEDIUM	MEDIUM
VERY HIGH	HIGH	LOW	HIGH
VERY HIGH	MEDIUM	HIGH	LOW
VERY HIGH	MEDIUM	MEDIUM	MEDIUM
VERY HIGH	MEDIUM	LOW	HIGH
VERY HIGH	LOW	HIGH	MEDIUM
VERY HIGH	LOW	MEDIUM	HIGH
VERY HIGH	LOW	LOW	VERY HIGH
HIGH	HIGH	HIGH	MEDIUM
HIGH	HIGH	MEDIUM	MEDIUM
HIGH	HIGH	LOW	HIGH
HIGH	MEDIUM	HIGH	MEDIUM
HIGH	MEDIUM	MEDIUM	MEDIUM
HIGH	MEDIUM	LOW	HIGH
HIGH	LOW	HIGH	MEDIUM
HIGH	LOW	MEDIUM	HIGH
HIGH	LOW	LOW	HIGH
MEDIUM	HIGH	HIGH	LOW
MEDIUM	HIGH	MEDIUM	LOW
MEDIUM	HIGH	LOW	MEDIUM
MEDIUM	MEDIUM	HIGH	LOW
MEDIUM	MEDIUM	MEDIUM	LOW
MEDIUM	MEDIUM	LOW	MEDIUM
MEDIUM	LOW	HIGH	LOW
MEDIUM	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	MEDIUM
LOW	HIGH	HIGH	LOW
LOW	HIGH	MEDIUM	LOW
LOW	HIGH	LOW	LOW
LOW	MEDIUM	HIGH	LOW
LOW	MEDIUM	MEDIUM	LOW
LOW	MEDIUM	LOW	LOW
LOW	LOW	HIGH	LOW
LOW	LOW	MEDIUM	LOW
LOW	LOW	LOW	LOW
VERY LOW	HIGH	HIGH	VERY LOW
VERY LOW	HIGH	MEDIUM	VERY LOW
VERY LOW	HIGH	LOW	VERY LOW
VERY LOW	MEDIUM	HIGH	VERY LOW
VERY LOW	MEDIUM	MEDIUM	VERY LOW
VERY LOW	MEDIUM	LOW	LOW
VERY LOW	LOW	HIGH	VERY LOW
VERY LOW	LOW	MEDIUM	VERY LOW
VERY LOW	LOW	LOW	LOW

Table A3: Rules for Press Mix Temperature from Expert Advice

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
HIGH	HIGH	HIGH	VERY HIGH	LOW
HIGH	HIGH	HIGH	HIGH	MEDIUM
HIGH	HIGH	HIGH	MEDIUM	MEDIUM
HIGH	HIGH	HIGH	LOW	HIGH
HIGH	HIGH	HIGH	VERY LOW	VERY HIGH
HIGH	HIGH	MEDIUM	VERY HIGH	LOW
HIGH	HIGH	MEDIUM	HIGH	LOW
HIGH	HIGH	MEDIUM	MEDIUM	MEDIUM
HIGH	HIGH	MEDIUM	LOW	HIGH
HIGH	HIGH	MEDIUM	VERY LOW	VERY HIGH
HIGH	HIGH	LOW	VERY HIGH	VERY LOW
HIGH	HIGH	LOW	HIGH	LOW
HIGH	HIGH	LOW	MEDIUM	MEDIUM
HIGH	HIGH	LOW	LOW	MEDIUM
HIGH	HIGH	LOW	VERY LOW	HIGH
HIGH	MEDIUM	HIGH	VERY HIGH	LOW
HIGH	MEDIUM	HIGH	HIGH	LOW
HIGH	MEDIUM	HIGH	MEDIUM	MEDIUM
HIGH	MEDIUM	HIGH	LOW	HIGH
HIGH	MEDIUM	HIGH	VERY LOW	HIGH
HIGH	MEDIUM	MEDIUM	VERY HIGH	VERY LOW
HIGH	MEDIUM	MEDIUM	HIGH	LOW
HIGH	MEDIUM	MEDIUM	MEDIUM	MEDIUM
HIGH	MEDIUM	MEDIUM	LOW	MEDIUM
HIGH	MEDIUM	MEDIUM	VERY LOW	HIGH
HIGH	MEDIUM	LOW	VERY HIGH	VERY LOW
HIGH	MEDIUM	LOW	HIGH	LOW
HIGH	MEDIUM	LOW	MEDIUM	MEDIUM
HIGH	MEDIUM	LOW	LOW	MEDIUM
HIGH	MEDIUM	LOW	VERY LOW	HIGH
HIGH	LOW	HIGH	VERY HIGH	VERY LOW
HIGH	LOW	HIGH	HIGH	LOW
HIGH	LOW	HIGH	MEDIUM	LOW
HIGH	LOW	HIGH	LOW	MEDIUM
HIGH	LOW	HIGH	VERY LOW	MEDIUM
HIGH	LOW	MEDIUM	VERY HIGH	VERY LOW
HIGH	LOW	MEDIUM	HIGH	LOW
HIGH	LOW	MEDIUM	MEDIUM	MEDIUM
HIGH	LOW	MEDIUM	LOW	MEDIUM
HIGH	LOW	MEDIUM	VERY LOW	HIGH
HIGH	LOW	LOW	VERY HIGH	VERY LOW
HIGH	LOW	LOW	HIGH	LOW
HIGH	LOW	LOW	MEDIUM	LOW
HIGH	LOW	LOW	LOW	MEDIUM
HIGH	LOW	LOW	LOW	MEDIUM

Table A4: Rules for Green Bulk Density from Expert Advice (Contd ..)

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
MEDIUM	HIGH	HIGH	VERY HIGH	LOW
MEDIUM	HIGH	HIGH	HIGH	LOW
MEDIUM	HIGH	HIGH	MEDIUM	MEDIUM
MEDIUM	HIGH	HIGH	LOW	HIGH
MEDIUM	HIGH	HIGH	VERY LOW	VERY HIGH
MEDIUM	HIGH	MEDIUM	VERY HIGH	VERY LOW
MEDIUM	HIGH	MEDIUM	HIGH	LOW
MEDIUM	HIGH	MEDIUM	MEDIUM	MEDIUM
MEDIUM	HIGH	MEDIUM	LOW	HIGH
MEDIUM	HIGH	MEDIUM	VERY LOW	VERY HIGH
MEDIUM	HIGH	LOW	VERY HIGH	VERY LOW
MEDIUM	HIGH	LOW	HIGH	LOW
MEDIUM	HIGH	LOW	MEDIUM	LOW
MEDIUM	HIGH	LOW	LOW	MEDIUM
MEDIUM	HIGH	LOW	VERY LOW	HIGH
MEDIUM	MEDIUM	HIGH	VERY HIGH	VERY LOW
MEDIUM	MEDIUM	HIGH	MEDIUM	LOW
MEDIUM	MEDIUM	HIGH	MEDIUM	MEDIUM
MEDIUM	MEDIUM	HIGH	LOW	HIGH
MEDIUM	MEDIUM	HIGH	VERY LOW	HIGH
MEDIUM	MEDIUM	MEDIUM	VERY HIGH	VERY LOW
MEDIUM	MEDIUM	MEDIUM	HIGH	LOW
MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
MEDIUM	MEDIUM	MEDIUM	LOW	MEDIUM
MEDIUM	MEDIUM	MEDIUM	VERY LOW	HIGH
MEDIUM	MEDIUM	LOW	VERY HIGH	VERY LOW
MEDIUM	MEDIUM	LOW	HIGH	LOW
MEDIUM	MEDIUM	LOW	MEDIUM	LOW
MEDIUM	MEDIUM	LOW	LOW	MEDIUM
MEDIUM	MEDIUM	LOW	VERY LOW	MEDIUM
MEDIUM	LOW	HIGH	VERY HIGH	VERY LOW
MEDIUM	LOW	HIGH	HIGH	VERY LOW
MEDIUM	LOW	HIGH	MEDIUM	LOW
MEDIUM	LOW	HIGH	LOW	MEDIUM
MEDIUM	LOW	HIGH	VERY LOW	MEDIUM
MEDIUM	LOW	MEDIUM	VERY HIGH	VERY LOW
MEDIUM	LOW	MEDIUM	HIGH	VERY LOW
MEDIUM	LOW	MEDIUM	MEDIUM	LOW
MEDIUM	LOW	MEDIUM	LOW	MEDIUM
MEDIUM	LOW	MEDIUM	VERY LOW	MEDIUM
MEDIUM	LOW	LOW	VERY HIGH	VERY LOW
MEDIUM	LOW	LOW	HIGH	VERY LOW
MEDIUM	LOW	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	LOW	LOW
MEDIUM	LOW	LOW	LOW	MEDIUM

Table A4 (Contd.): Rules for Green Bulk Density from Expert Advice (Contd…)

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
LOW	HIGH	HIGH	VERY HIGH	VERY LOW
LOW	HIGH	HIGH	HIGH	LOW
LOW	HIGH	HIGH	MEDIUM	MEDIUM
LOW	HIGH	HIGH	LOW	MEDIUM
LOW	HIGH	HIGH	VERY LOW	HIGH
LOW	HIGH	MEDIUM	VERY HIGH	VERY LOW
LOW	HIGH	MEDIUM	HIGH	VERY LOW
LOW	HIGH	MEDIUM	MEDIUM	LOW
LOW	HIGH	MEDIUM	LOW	MEDIUM
LOW	HIGH	MEDIUM	VERY LOW	HIGH
LOW	HIGH	LOW	VERY HIGH	VERY LOW
LOW	HIGH	LOW	HIGH	VERY LOW
LOW	HIGH	LOW	MEDIUM	LOW
LOW	HIGH	LOW	LOW	LOW
LOW	HIGH	LOW	VERY LOW	MEDIUM
LOW	MEDIUM	HIGH	VERY HIGH	VERY LOW
LOW	MEDIUM	HIGH	HIGH	LOW
LOW	MEDIUM	HIGH	MEDIUM	MEDIUM
LOW	MEDIUM	HIGH	LOW	HIGH
LOW	MEDIUM	HIGH	VERY LOW	HIGH
LOW	MEDIUM	MEDIUM	VERY HIGH	VERY LOW
LOW	MEDIUM	MEDIUM	HIGH	VERY LOW
LOW	MEDIUM	MEDIUM	MEDIUM	LOW
LOW	MEDIUM	MEDIUM	LOW	MEDIUM
LOW	MEDIUM	MEDIUM	VERY LOW	MEDIUM
LOW	MEDIUM	LOW	VERY HIGH	VERY LOW
LOW	MEDIUM	LOW	HIGH	VERY LOW
LOW	MEDIUM	LOW	MEDIUM	LOW
LOW	MEDIUM	LOW	LOW	MEDIUM
LOW	MEDIUM	LOW	VERY LOW	MEDIUM
LOW	LOW	HIGH	VERY HIGH	VERY LOW
LOW	LOW	HIGH	HIGH	VERY LOW
LOW	LOW	HIGH	MEDIUM	LOW
LOW	LOW	HIGH	LOW	LOW
LOW	LOW	HIGH	VERY LOW	MEDIUM
LOW	LOW	MEDIUM	VERY HIGH	VERY LOW
LOW	LOW	MEDIUM	HIGH	VERY LOW
LOW	LOW	MEDIUM	MEDIUM	LOW
LOW	LOW	MEDIUM	LOW	MEDIUM
LOW	LOW	MEDIUM	VERY LOW	MEDIUM
LOW	LOW	LOW	VERY HIGH	VERY LOW
LOW	LOW	LOW	HIGH	VERY LOW
LOW	LOW	LOW	MEDIUM	VERY LOW
LOW	LOW	LOW	LOW	LOW
LOW	LOW	LOW	LOW	LOW

Table A4 (Contd.). Rules for Green Bulk Density from Expert Advice

GREEN BULK DENSITY (GBD)	PITCH QUANTITY (PQ)	TEMPERING STATUS (TS)	COLD CRUSHING STRENGTH (CCS)
VERY HIGH	HIGH	PERFECT	VERY HIGH
VERY HIGH	HIGH	UNDER	VERY HIGH
VERY HIGH	HIGH	OVER	HIGH
VERY HIGH	MEDIUM	PERFECT	VERY HIGH
VERY HIGH	MEDIUM	UNDER	HIGH
VERY HIGH	MEDIUM	OVER	HIGH
VERY HIGH	LOW	PERFECT	HIGH
VERY HIGH	LOW	UNDER	MEDIUM
VERY HIGH	LOW	OVER	VERY HIGH
HIGH	HIGH	PERFECT	VERY HIGH
HIGH	HIGH	UNDER	HIGH
HIGH	HIGH	OVER	HIGH
HIGH	MEDIUM	PERFECT	HIGH
HIGH	MEDIUM	UNDER	MEDIUM
HIGH	MEDIUM	OVER	MEDIUM
HIGH	LOW	PERFECT	MEDIUM
HIGH	LOW	UNDER	MEDIUM
HIGH	LOW	OVER	MEDIUM
MEDIUM	HIGH	PERFECT	HIGH
MEDIUM	HIGH	UNDER	HIGH
MEDIUM	HIGH	OVER	MEDIUM
MEDIUM	MEDIUM	PERFECT	MEDIUM
MEDIUM	MEDIUM	UNDER	MEDIUM
MEDIUM	MEDIUM	OVER	LOW
MEDIUM	LOW	PERFECT	LOW
MEDIUM	LOW	UNDER	MEDIUM
MEDIUM	LOW	OVER	LOW
LOW	HIGH	PERFECT	MEDIUM
LOW	HIGH	UNDER	MEDIUM
LOW	HIGH	OVER	LOW
LOW	MEDIUM	PERFECT	MEDIUM
LOW	MEDIUM	UNDER	MEDIUM
LOW	MEDIUM	OVER	LOW
LOW	LOW	PERFECT	LOW
LOW	LOW	UNDER	LOW
LOW	LOW	OVER	VERY LOW
VERY LOW	HIGH	PERFECT	VERY LOW
VERY LOW	HIGH	UNDER	LOW
VERY LOW	HIGH	OVER	VERY LOW
VERY LOW	MEDIUM	PERFECT	VERY LOW
VERY LOW	MEDIUM	UNDER	LOW
VERY LOW	MEDIUM	OVER	VERY LOW
VERY LOW	LOW	PERFECT	VERY LOW
VERY LOW	LOW	UNDER	VERY LOW
VERY LOW	LOW	OVER	VERY LOW

Table A5: Rules for Cold Crushing Strength from Expert Advice

GREEN BULK DENSITY (GBD)	PITCH QUANTITY (PQ)	COKED POROSITY (CP)
VERY_HIGH	HIGH	MEDIUM
VERY_HIGH	MEDIUM	LOW
VERY_HIGH	LOW	LOW
HIGH	HIGH	HIGH
HIGH	MEDIUM	MEDIUM
HIGH	LOW	LOW
MEDIUM	HIGH	HIGH
MEDIUM	MEDIUM	MEDIUM
MEDIUM	LOW	MEDIUM
LOW	HIGH	HIGH
LOW	MEDIUM	MEDIUM
LOW	LOW	MEDIUM
VERY_LOW	HIGH	HIGH
VERY_LOW	MEDIUM	HIGH
VERY_LOW	LOW	HIGH

Table A6: Rules for Coked Porosity from Expert Advice

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
VERY HIGH	LOW	HIGH	HIGH	VERY VERY HIGH
VERY HIGH	LOW	HIGH	MEDIUM	VERY VERY HIGH
VERY HIGH	LOW	HIGH	LOW	VERY VERY HIGH
VERY HIGH	LOW	MEDIUM	HIGH	VERY VERY HIGH
VERY HIGH	LOW	MEDIUM	MEDIUM	VERY VERY HIGH
VERY HIGH	LOW	MEDIUM	LOW	VERY HIGH
VERY HIGH	LOW	LOW	HIGH	HIGH
VERY HIGH	LOW	LOW	MEDIUM	HIGH
VERY HIGH	LOW	LOW	LOW	MEDIUM
VERY HIGH	VERY LOW	HIGH	HIGH	VERY VERY HIGH
VERY HIGH	VERY LOW	HIGH	MEDIUM	VERY HIGH
VERY HIGH	VERY LOW	HIGH	LOW	VERY HIGH
VERY HIGH	VERY LOW	MEDIUM	HIGH	HIGH
VERY HIGH	VERY LOW	MEDIUM	MEDIUM	HIGH
VERY HIGH	VERY LOW	MEDIUM	LOW	HIGH
VERY HIGH	VERY LOW	LOW	HIGH	MEDIUM
VERY HIGH	VERY LOW	LOW	MEDIUM	MEDIUM
VERY HIGH	VERY LOW	LOW	LOW	MEDIUM
HIGH	MEDIUM	HIGH	HIGH	VERY VERY HIGH
HIGH	MEDIUM	HIGH	MEDIUM	VERY VERY HIGH
HIGH	MEDIUM	HIGH	LOW	VERY VERY HIGH
HIGH	MEDIUM	MEDIUM	HIGH	VERY VERY HIGH
HIGH	MEDIUM	MEDIUM	MEDIUM	VERY VERY HIGH
HIGH	MEDIUM	MEDIUM	LOW	VERY HIGH
HIGH	MEDIUM	LOW	HIGH	HIGH
HIGH	MEDIUM	LOW	MEDIUM	MEDIUM
HIGH	MEDIUM	LOW	LOW	MEDIUM
HIGH	LOW	HIGH	HIGH	VERY VERY HIGH
HIGH	LOW	HIGH	MEDIUM	VERY VERY HIGH
HIGH	LOW	HIGH	LOW	VERY HIGH
HIGH	LOW	MEDIUM	HIGH	VERY HIGH
HIGH	LOW	MEDIUM	MEDIUM	VERY HIGH
HIGH	LOW	MEDIUM	LOW	HIGH
HIGH	LOW	LOW	HIGH	HIGH

Table A7: Rules for HMOR from Expert Advice (Contd…)

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
HIGH	LOW	LOW	MEDIUM	MEDIUM
HIGH	LOW	LOW	LOW	MEDIUM
HIGH	VERY LOW	HIGH	HIGH	VERY HIGH
HIGH	VERY LOW	HIGH	MEDIUM	VERY HIGH
HIGH	VERY LOW	HIGH	LOW	VERY HIGH
HIGH	VERY LOW	MEDIUM	HIGH	HIGH
HIGH	VERY LOW	MEDIUM	MEDIUM	HIGH
HIGH	VERY LOW	MEDIUM	LOW	MEDIUM
HIGH	VERY LOW	LOW	HIGH	MEDIUM
HIGH	VERY LOW	LOW	MEDIUM	MEDIUM
HIGH	VERY LOW	LOW	LOW	MEDIUM
MEDIUM	MEDIUM	HIGH	HIGH	VERY VERY HIGH
MEDIUM	MEDIUM	HIGH	MEDIUM	VERY VERY HIGH
MEDIUM	MEDIUM	HIGH	LOW	VERY VERY HIGH
MEDIUM	MEDIUM	MEDIUM	HIGH	VERY VERY HIGH
MEDIUM	MEDIUM	MEDIUM	MEDIUM	VERY HIGH
MEDIUM	MEDIUM	MEDIUM	LOW	HIGH
MEDIUM	MEDIUM	LOW	HIGH	MEDIUM
MEDIUM	MEDIUM	LOW	MEDIUM	MEDIUM
MEDIUM	MEDIUM	LOW	LOW	LOW
MEDIUM	LOW	HIGH	HIGH	VERY HIGH
MEDIUM	LOW	HIGH	MEDIUM	VERY HIGH
MEDIUM	LOW	HIGH	LOW	VERY HIGH
MEDIUM	LOW	MEDIUM	HIGH	VERY HIGH
MEDIUM	LOW	MEDIUM	MEDIUM	VERY HIGH
MEDIUM	LOW	MEDIUM	LOW	HIGH
MEDIUM	LOW	LOW	HIGH	MEDIUM
MEDIUM	LOW	LOW	MEDIUM	MEDIUM
MEDIUM	LOW	LOW	LOW	LOW
MEDIUM	VERY LOW	HIGH	HIGH	HIGH
MEDIUM	VERY LOW	HIGH	MEDIUM	MEDIUM
MEDIUM	VERY LOW	HIGH	LOW	MEDIUM
MEDIUM	VERY LOW	MEDIUM	HIGH	MEDIUM
MEDIUM	VERY LOW	MEDIUM	MEDIUM	MEDIUM
MEDIUM	VERY LOW	MEDIUM	LOW	LOW
MEDIUM	VERY LOW	LOW	HIGH	LOW

Table A7 (Contd.): Rules for HMOR from Expert Advice (Contd…)

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
MEDIUM	VERY LOW	LOW	MEDIUM	VERY LOW
MEDIUM	VERY LOW	LOW	LOW	VERY LOW
LOW	HIGH	HIGH	HIGH	VERY HIGH
LOW	HIGH	HIGH	MEDIUM	VERY HIGH
LOW	HIGH	HIGH	LOW	HIGH
LOW	HIGH	MEDIUM	HIGH	HIGH
LOW	HIGH	MEDIUM	MEDIUM	HIGH
LOW	HIGH	MEDIUM	LOW	HIGH
LOW	HIGH	LOW	HIGH	MEDIUM
LOW	HIGH	LOW	MEDIUM	MEDIUM
LOW	HIGH	LOW	LOW	LOW
LOW	MEDIUM	HIGH	HIGH	VERY HIGH
LOW	MEDIUM	HIGH	MEDIUM	VERY HIGH
LOW	MEDIUM	HIGH	LOW	VERY HIGH
LOW	MEDIUM	MEDIUM	HIGH	HIGH
LOW	MEDIUM	MEDIUM	MEDIUM	HIGH
LOW	MEDIUM	MEDIUM	LOW	HIGH
LOW	MEDIUM	LOW	HIGH	MEDIUM
LOW	MEDIUM	LOW	MEDIUM	LOW
LOW	MEDIUM	LOW	LOW	LOW
LOW	LOW	HIGH	HIGH	VERY HIGH
LOW	LOW	HIGH	MEDIUM	VERY HIGH
LOW	LOW	HIGH	LOW	HIGH
LOW	LOW	MEDIUM	HIGH	HIGH
LOW	LOW	MEDIUM	MEDIUM	HIGH
LOW	LOW	MEDIUM	LOW	MEDIUM
LOW	LOW	LOW	HIGH	LOW
LOW	LOW	LOW	MEDIUM	VERY LOW
LOW	LOW	LOW	LOW	VERY LOW
VERY LOW	VERY HIGH	HIGH	HIGH	HIGH
VERY LOW	VERY HIGH	HIGH	MEDIUM	HIGH
VERY LOW	VERY HIGH	HIGH	LOW	MEDIUM
VERY LOW	VERY HIGH	MEDIUM	HIGH	MEDIUM
VERY LOW	VERY HIGH	MEDIUM	MEDIUM	MEDIUM
VERY LOW	VERY HIGH	MEDIUM	LOW	MEDIUM
VERY LOW	VERY HIGH	LOW	HIGH	LOW
VERY LOW	VERY HIGH	LOW	MEDIUM	LOW
VERY LOW	VERY HIGH	LOW	LOW	LOW

Table A7 (Contd.)· Rules for HMOR from Expert Advice

RETAINED CARBON (RC)	CHEMICAL PURITY (CHP)	COKED POROSITY (CP)	SLAG CORROSION RESISTANCE (SCR)
MEDIUM	HIGH	HIGH	MEDIUM
MEDIUM	HIGH	MEDIUM	HIGH
MEDIUM	HIGH	LOW	HIGH
MEDIUM	MEDIUM	HIGH	MEDIUM
MEDIUM	MEDIUM	MEDIUM	MEDIUM
MEDIUM	MEDIUM	LOW	HIGH
MEDIUM	LOW	HIGH	LOW
MEDIUM	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	LOW
LOW	HIGH	HIGH	LOW
LOW	HIGH	MEDIUM	MEDIUM
LOW	HIGH	LOW	MEDIUM
LOW	MEDIUM	HIGH	LOW
LOW	MEDIUM	MEDIUM	MEDIUM
LOW	MEDIUM	LOW	MEDIUM
LOW	LOW	HIGH	VERY LOW
LOW	LOW	MEDIUM	VERY LOW
LOW	LOW	LOW	LOW
VERY LOW	HIGH	HIGH	LOW
VERY LOW	HIGH	MEDIUM	MEDIUM
VERY LOW	HIGH	LOW	MEDIUM
VERY LOW	MEDIUM	HIGH	VERY LOW
VERY LOW	MEDIUM	MEDIUM	LOW
VERY LOW	MEDIUM	LOW	LOW
VERY LOW	LOW	HIGH	VERY LOW
VERY LOW	LOW	MEDIUM	VERY LOW
VERY LOW	LOW	LOW	LOW
VERY HIGH	HIGH	HIGH	HIGH
VERY HIGH	HIGH	MEDIUM	VERY HIGH
VERY HIGH	HIGH	LOW	VERY HIGH
VERY HIGH	MEDIUM	HIGH	HIGH
VERY HIGH	MEDIUM	MEDIUM	HIGH
VERY HIGH	MEDIUM	LOW	VERY HIGH
VERY HIGH	LOW	HIGH	LOW
VERY HIGH	LOW	MEDIUM	MEDIUM
VERY HIGH	LOW	LOW	MEDIUM
HIGH	HIGH	HIGH	HIGH
HIGH	HIGH	MEDIUM	HIGH
HIGH	HIGH	LOW	VERY HIGH
HIGH	MEDIUM	HIGH	HIGH
HIGH	MEDIUM	MEDIUM	HIGH
HIGH	MEDIUM	LOW	VERY HIGH
HIGH	LOW	HIGH	LOW
HIGH	LOW	MEDIUM	LOW
HIGH	LOW	LOW	MEDIUM

Table A8: Rules for Slag Corrosion Resistance from Expert Advice

GREEN BULK DENSITY (GBD)	RETAINED CARBON (RC)	METAL POWDER (MP)	OXIDATION RESISTANCE (OR)
VERY HIGH	VERY LOW	HIGH	MEDIUM
VERY HIGH	VERY LOW	MEDIUM	LOW
VERY HIGH	VERY LOW	LOW	VERY LOW
HIGH	VERY LOW	HIGH	LOW
HIGH	VERY LOW	MEDIUM	VERY LOW
HIGH	VERY LOW	LOW	VERY LOW
HIGH	LOW	HIGH	MEDIUM
HIGH	LOW	MEDIUM	LOW
HIGH	LOW	LOW	LOW
MEDIUM	HIGH	HIGH	VERY HIGH
MEDIUM	HIGH	MEDIUM	HIGH
MEDIUM	HIGH	LOW	MEDIUM
MEDIUM	MEDIUM	HIGH	HIGH
MEDIUM	MEDIUM	MEDIUM	HIGH
MEDIUM	MEDIUM	LOW	MEDIUM
MEDIUM	LOW	HIGH	MEDIUM
MEDIUM	LOW	MEDIUM	LOW
MEDIUM	LOW	LOW	LOW
MEDIUM	VERY LOW	HIGH	LOW
MEDIUM	VERY LOW	MEDIUM	LOW
MEDIUM	VERY LOW	LOW	VERY LOW
LOW	VERY HIGH	HIGH	VERY HIGH
LOW	VERY HIGH	MEDIUM	VERY HIGH
LOW	VERY HIGH	LOW	HIGH
LOW	VERY LOW	HIGH	LOW
LOW	VERY LOW	MEDIUM	VERY LOW
LOW	VERY LOW	LOW	VERY LOW
LOW	HIGH	HIGH	HIGH
LOW	HIGH	MEDIUM	HIGH
LOW	HIGH	LOW	MEDIUM
LOW	MEDIUM	HIGH	MEDIUM
LOW	MEDIUM	MEDIUM	LOW
LOW	MEDIUM	LOW	LOW
LOW	LOW	HIGH	LOW
LOW	LOW	MEDIUM	VERY LOW
LOW	LOW	LOW	VERY LOW
VERY LOW	HIGH	HIGH	MEDIUM
VERY LOW	HIGH	MEDIUM	MEDIUM
VERY LOW	HIGH	LOW	LOW
VERY LOW	MEDIUM	HIGH	MEDIUM
VERY LOW	MEDIUM	MEDIUM	LOW
VERY LOW	MEDIUM	LOW	LOW
VERY LOW	VERY HIGH	HIGH	VERY HIGH
VERY LOW	VERY HIGH	MEDIUM	HIGH
VERY LOW	VERY HIGH	LOW	MEDIUM

Table A9: Rules for Oxidation Resistance from Expert Advice

RULE BASE FROM ID3 PROGRAM

```
classes([high,medium,low]).
attributes([cct,ghdt,rt]).

example(  1,  very_high  ,[cct=  high    ,ghdt=  high    ,rt=  high    ])
example(  2,  high       ,[cct=  high    ,ghdt=  high    ,rt=  medium  ])
example(  3,  medium     ,[cct=  high    ,ghdt=  high    ,rt=  low     ])
example(  4,  high       ,[cct=  high    ,ghdt=  medium  ,rt=  high    ])
example(  5,  medium     ,[cct=  high    ,ghdt=  medium  ,rt=  medium  ])
example(  6,  medium     ,[cct=  high    ,ghdt=  medium  ,rt=  low     ])
example(  7,  medium     ,[cct=  high    ,ghdt=  low     ,rt=  high    ])
example(  8,  low        ,[cct=  high    ,ghdt=  low     ,rt=  medium  ])
example(  9,  very_low   ,[cct=  high    ,ghdt=  low     ,rt=  low     ])
example( 10,  very_high  ,[cct=  medium  ,ghdt=  high    ,rt=  high    ])
example( 11,  high       ,[cct=  medium  ,ghdt=  high    ,rt=  medium  ])
example( 12,  medium     ,[cct=  medium  ,ghdt=  high    ,rt=  low     ])
example( 13,  high       ,[cct=  medium  ,ghdt=  medium  ,rt=  high    ])
example( 14,  medium     ,[cct=  medium  ,ghdt=  medium  ,rt=  medium  ])
example( 15,  low        ,[cct=  medium  ,ghdt=  medium  ,rt=  low     ])
example( 16,  medium     ,[cct=  medium  ,ghdt=  low     ,rt=  high    ])
example( 17,  low        ,[cct=  medium  ,ghdt=  low     ,rt=  medium  ])
example( 18,  very_low   ,[cct=  medium  ,ghdt=  low     ,rt=  low     ])
example( 19,  high       ,[cct=  low     ,ghdt=  high    ,rt=  high    ])
example( 20,  medium     ,[cct=  low     ,ghdt=  high    ,rt=  medium  ])
example( 21,  low        ,[cct=  low     ,ghdt=  high    ,rt=  low     ])
example( 22,  medium     ,[cct=  low     ,ghdt=  medium  ,rt=  high    ])
example( 23,  medium     ,[cct=  low     ,ghdt=  medium  ,rt=  medium  ])
example( 24,  low        ,[cct=  low     ,ghdt=  medium  ,rt=  low     ])
example( 25,  low        ,[cct=  low     ,ghdt=  low     ,rt=  high    ])
example( 26,  very_low   ,[cct=  low     ,ghdt=  low     ,rt=  medium  ])
example( 27,  very_low   ,[cct=  low     ,ghdt=  low     ,rt=  low     ])
```

Table B1: Format for ID3 Rule Generation for Table A1

```
fuzzy_matrix( grain_temp_value ) -
combustion_chamber_temp * grain_heater_drum_temp * grain_heater_retention_time -> grain_temp ,

high     *    high     *    high     ->    very_high    ,
high     *    high     *    medium   ->    high         ,
high     *    high     *    low      ->    medium       ,
high     *    medium   *    high     ->    high         ,
high     *    medium   *    medium   ->    medium       ,
high     *    medium   *    low      ->    medium       ,
high     *    low      *    high     ->    medium       ,
high     *    low      *    medium   ->    low          ,
high     *    low      *    low      ->    very_low     ,
medium   *    high     *    high     ->    very_high    ,
medium   *    high     *    medium   ->    high         ,
medium   *    high     *    low      ->    medium       ,
medium   *    medium   *    high     ->    high         ,
medium   *    medium   *    medium   ->    medium       ,
medium   *    medium   *    low      ->    low          ,
medium   *    low      *    high     ->    medium       ,
medium   *    low      *    medium   ->    low          ;
medium   *    low      *    low      ->    very_low     ,
low      *    high     *    high     ->    high         ,
low      *    high     *    medium   ->    medium       ,
low      *    high     *    low      ->    low          ,
low      *    medium   *    high     ->    medium       ,
low      *    medium   *    medium   ->    medium       ,
low      *    medium   *    low      ->    low          ;
low      *    low      *    high     ->    low          ,
low      *    low      *    medium   ->    very_low     ,
low      *    low      *    low      ->    very_low     .
```

Table B2. Format for storing rules from Table A1 as Fuzzy Matrix

ghdt = high and rt = high and cct = high ==> class = very_high
cct = medium ==> class = very_high
cct = low ==> class = high

rt = medium and cct = high ==> class = high
cct = medium ==> class = high
cct = low ==> class = medium

rt = low and cct = high ==> class = medium
cct = medium ==> class = medium
cct = low ==> class = low

ghdt = medium and rt = high and cct = high ==> class = high
cct = medium ==> class = high
cct = low ==> class = medium

rt = medium ==> class = medium

rt = low and cct = high ==> class = medium
cct = medium ==> class = low
cct = low ==> class = low

ghdt = low and rt = high and cct = high ==> class = medium
cct = medium ==> class = medium
cct = low ==> class = low

rt = medium and cct = high ==> class = low
cct = medium ==> class = low
cct = low ==> class = very_low

rt = low ==> class = very_low

Figure B1: Decision Tree for Grain Temperature of Table A1

gt = very_high ==> class = very_high
gt = high and mixer_temp = high ==> class = high
mixer_temp = medium ==> class = high
mixer_temp = low and mix_time = high ==> class = high
mix_time = medium ==> class = high
mix_time = low ==> class = medium

gt = medium and mixer_temp = high ==> class = medium
mixer_temp = medium ==> class = medium
mixer_temp = low and mix_time = high ==> class = low
mix_time = medium ==> class = low
mix_time = low ==> class = medium

gt = low and mixer_temp = high and mix_time = high ==> class = medium
mix_time = medium ==> class = low
mix_time = low ==> class = low

mixer_temp = medium ==> class = low
mixer_temp = low ==> class = low

gt = very_low and mixer_temp = high and mix_time = high ==> class = low
mix_time = medium ==> class = low
mix_time = low ==> class = very_low

mixer_temp = medium and mix_time = high ==> class = low
mix_time = medium ==> class =
low
mix_time = low ==> class =
very_low

mixer_temp = low ==> class = very_low

Figure B2: Decision Tree for Mix Temperature of table A2

```
mix_temp = very_high and    rolls = high and    st = high ==> class = low
                                                st = medium ==> class = low
                                                st = low ==> class = medium

                            rolls = medium and  st = high ==> class = medium
                                                st = medium ==> class = medium
                                                st = low ==> class = high

                            rolls = low and     st = high ==> class = high
                                                st = medium ==> class = high
                                                st = low ==> class = very_high

mix_temp = high and      rolls = high ==> class = medium
                         rolls = medium and   st = high ==> class = medium
                                              st = medium ==> class = medium
                                              st = low ==> class = high

                         rolls = low ==> class = high

mix_temp = medium and    rolls = high ==> class = low
                         rolls = medium ==> class = low
                         rolls = low ==> class = medium

mix_temp = low ==> class = low
mix_temp = very_low and  rolls = high ==> class = very_low
                         rolls = medium ==> class = very_low
                         rolls = low and   st = high ==> class = very_low
                                           st = medium ==> class = low
                                           st = low ==> class = low
```

Figure B3: Decision Tree for Press Mix Temperature of table A3

```
graphite = very_low and pmt = high and     fp = high and     pitch = high  ==> class = very_high
                                                             pitch = medium  ==> class = very_high
                                                             pitch = low  ==> class = high

                                           fp = medium and   pitch = high  ==> class = very_high
                                                             pitch = medium  ==> class = very_high
                                                             pitch = low  ==> class = high

                                           fp = low and      pitch = high  ==> class = high
                                                             pitch = medium  ==> class = high
                                                             pitch = low  ==> class = medium

                   pmt = medium and        fp = high  ==> class = high
                                           fp = medium and   pitch = high  ==> class = high
                                                             pitch = medium  ==> class = high
                                                             pitch = low  ==> class = medium

                                           fp = low and      pitch = high  ==> class = high
                                                             pitch = medium  ==> class = medium
                                                             pitch = low  ==> class = medium

                   pmt = low and    pitch = high  ==> class = medium
                                    pitch = medium and       fp = high  ==> class = high
                                                             fp = medium  ==> class = medium
                                                             fp = low  ==> class = medium

graphite = very_high and fp = high and     pmt = high and    pitch = high  ==> class = low
                                                             pitch = medium  ==> class = low
                                                             pitch = low  ==> class = very_low

                                           pmt = medium and pitch = high  ==> class = low
                                                             pitch = medium  ==> class = very_low
                                                             pitch = low  ==> class = very_low

                                           pmt = low  ==> class = very_low

                    fp = medium and        pmt = high and pitch = high  ==> class = low
                                                          pitch = medium  ==> class = very_low
                                                          pitch = low  ==> class = very_low

                                           pmt = medium  ==> class = very_low
                                           pmt = low  ==> class = very_low

                    fp = low  ==> class = very_low
```

Figure B4: Decision Tree for Green Bulk Density of table A4(Contd…)

```
graphite = high and    fp = high and    pmt = high and    pitch = high ==> class = medium
                                                          pitch = medium ==> class = low
                                                          pitch = low ==> class = low

                                        pmt = medium ==> class = low
                                        pmt = low ==> class = low

                       fp = medium and pmt = high ==> class = low
                                       pmt = medium ==> class = low
                                       pmt = low ==> class = very_low

                       fp = low and     pitch = high and pmt = high ==> class = low
                                                         pmt = medium ==> class = low
                                                         pmt = low ==> class = very_low

                                        pitch = medium ==> class = very_low
                                        pitch = low ==> class = very_low


graphite = medium and pmt = high and fp = high ==> class = medium
                                     fp = medium and pitch = high ==> class = medium
                                                     pitch = medium ==> class = medium
                                                     pitch = low ==> class = low

                                     fp = low and    pitch = high ==> class = medium
                                                     pitch = medium ==> class = low
                                                     pitch = low ==> class = low


                      pmt = medium and  fp = high ==> class = medium
                                        fp = medium and pitch = high ==> class = medium
                                                        pitch = medium ==> class = medium
                                                        pitch = low ==> class = low

                                        fp = low and    pitch = high ==> class = medium
                                                        pitch = medium ==> class = low
                                                        pitch = low ==> class = low


                      pmt = low and     fp = high and   pitch = high ==> class = low
                                                        pitch = medium ==> class = medium
                                                        pitch = low ==> class = low

                                        fp = medium ==> class = low
                                        fp = low and    pitch = high ==> class = low
                                                        pitch = medium ==> class = low
                                                        pitch = low ==> class = very_low
```

Figure B4 (contd.): Decision Tree for Green Bulk Density of table A4 (Contd...)

graphite = low and pitch = high and
pmt = high and fp = high ==> class = high
fp = medium ==> class = high
fp = low ==> class = medium

pmt = medium ==> class = high
pmt = low and fp = high ==> class = medium
fp = medium ==> class = medium
fp = low ==> class = low

pitch = medium and
pmt = high and fp = high ==> class = high
fp = medium ==> class = high
fp = low ==> class = medium

pmt = medium ==> class = medium
pmt = low ==> class = medium

pitch = low and
pmt = high and fp = high ==> class = medium
fp = medium ==> class = medium
fp = low ==> class = low

pmt = medium ==> class = medium
pmt = low and fp = high ==> class = medium
fp = medium ==> class = medium
fp = low ==> class = low

Figure B4 (contd.): Decision Tree for Green Bulk Density of table A4

gbd = medium and pitch = high and tempering = perfect ==> class = high
tempering = under ==> class = high
tempering = over ==> class = medium

pitch = medium and tempering = perfect ==> class = medium
tempering = under ==> class = medium
tempering = over ==> class = low

pitch = low and tempering = perfect ==> class = low
tempering = under ==> class = medium
tempering = over ==> class = low

gbd = low and pitch = high and tempering = perfect ==> class = medium
tempering = under ==> class = medium
tempering = over ==> class = low

pitch = medium and tempering = perfect ==> class = medium
tempering = under ==> class = medium
tempering = over ==> class = low

pitch = low and tempering = perfect ==> class = low
tempering = under ==> class = low
tempering = over ==> class = very_low

gbd = very_low and tempering = perfect ==> class = very_low
tempering = under and pitch = high ==> class = low
pitch = medium ==> class = low
pitch = low ==> class = very_low

tempering = over ==> class = very_low

gbd = very_high and pitch = high and tempering = perfect ==> class = very_high
tempering = under ==> class = very_high
tempering = over ==> class = high

pitch = medium and tempering = perfect ==> class = very_high
tempering = under ==> class = high
tempering = over ==> class = high

pitch = low and tempering = perfect ==> class = high
tempering = under ==> class = medium
tempering = over ==> class = very_high

gbd = high and pitch = high and tempering = perfect ==> class = very_high
tempering = under ==> class = high
tempering = over ==> class = high

pitch = medium and tempering = perfect ==> class = high
tempering = under ==> class = medium
tempering = over ==> class = medium

pitch = low ==> class = medium

Figure B5: Decision Tree for Cold Crushing Strength of table A5

gbd = very_high and   pitch = high ==> class = medium
pitch = medium ==> class = low
pitch = low ==> class = low

gbd = high and pitch = high ==> class = high
pitch = medium ==> class = medium
pitch = low ==> class = low

gbd = medium and   pitch = high ==> class = high
pitch = medium ==> class = medium
pitch = low ==> class = medium

gbd = low and pitch = high ==> class = high
pitch = medium ==> class = medium
pitch = low ==> class = medium

gbd = very_low ==> class = high

Figure B6: Decision Tree for Coked Porosity of table A6

mp = high and   ccs = high and   gbd = very_low and   rc = very_high ==> class = vv_high
rc = high ==> class = very_high
rc = medium ==> class = high

gbd = high ==> class = very_high
gbd = medium and   rc = high ==> class = vv_high
rc = medium ==> class = vv_high
rc = low ==> class = very_high

gbd = low and   rc = very_high ==> class = vv_high
rc = high ==> class = vv_high
rc = medium ==> class = very_high
rc = low ==> class = very_high

gbd = very_high ==> class = high

ccs = medium and gbd = very_low and   rc = very_high ==> class = very_high
rc = high ==> class = very_high
rc = medium ==> class = medium

gbd = high ==> class = very_high
gbd = medium and   rc = high ==> class = vv_high
rc = medium ==> class = vv_high
rc = low ==> class = very_high

gbd = low and   rc = very_high ==> class = vv_high
rc = high ==> class = vv_high
rc = medium ==> class = very_high
rc = low ==> class = very_high

gbd = very_high ==> class = high

ccs = low and   gbd = very_low and   rc = very_high ==> class = very_high
rc = high ==> class = very_high
rc = medium ==> class = medium

gbd = high ==> class = high
gbd = medium and   rc = high ==> class = vv_high
rc = medium ==> class = vv_high
rc = low ==> class = very_high

gbd = low and   rc = very_high ==> class = vv_high
rc = high ==> class = very_high
rc = medium ==> class = very_high
rc = low ==> class = high

gbd = very_high ==> class = medium

Figure B7: Decision Tree for HMOR of table A7 (Contd…)

mp = medium and ccs = high and gbd = very_low and rc = very_high ==> class = high
rc = high ==> class = high
rc = medium ==> class = medium

gbd = high ==> class = high
gbd = medium and rc = high ==> class = vv_high
rc = medium ==> class = vv_high
rc = low ==> class = high

gbd = low and rc = very_high ==> class = vv_high
rc = high ==> class = very_high
rc = medium ==> class = very_high
rc = low ==> class = high

gbd = very_high ==> class = medium

ccs = medium and gbd = very_low and rc = very_high ==> class = high
rc = high ==> class = high
rc = medium ==> class = medium

gbd = high ==> class = high
gbd = medium and rc = high ==> class = vv_high
rc = medium ==> class = very_high
rc = low ==> class = high

gbd = low and rc = very_high ==> class = vv_high
rc = high ==> class = very_high
rc = medium ==> class = very_high
rc = low ==> class = high

gbd = very_high ==> class = medium

ccs = low and gbd = very_low and ic = very_high ==> class = high
rc = high ==> class = medium
rc = medium ==> class = low

gbd = high ==> class = high
gbd = medium and rc = high ==> class = very_high
rc = medium ==> class = high
rc = low ==> class = high

gbd = low and rc = very_high ==> class = very_high
rc = high ==> class = high
rc = medium ==> class = high
rc = low ==> class = medium

gbd = very_high ==> class = medium

Figure B7 (Contd.): Decision Tree for HMOR of table A7 (Contd..)

mp = low and rc = very_high and gbd = low and ccs = high ==> class = high
ccs = medium ==> class = high
ccs = low ==> class = medium

gbd = very_low ==> class = medium

rc = high and ccs = high and gbd = medium ==> class = high
gbd = low ==> class = high
gbd = very_low ==> class = medium

ccs = medium ==> class = medium
ccs = low ==> class = medium

rc = medium and gbd = medium and ccs = high ==> class = medium
ccs = medium ==> class = medium
ccs = low ==> class = low

gbd = low and ccs = high ==> class = medium
ccs = medium ==> class = medium
ccs = low ==> class = low

gbd = very_low and ccs = high ==> class = low
ccs = medium ==> class = very_low
ccs = low ==> class = very_low

rc = low and gbd = high and ccs = high ==> class = medium
ccs = medium ==> class = medium
ccs = low ==> class = low

gbd = medium and ccs = high ==> class = medium
ccs = medium ==> class = low
ccs = low ==> class = low

gbd = low and ccs = high ==> class = low
ccs = medium ==> class = very_low
ccs = low ==> class = very_low

rc = very_low ==> class = low

Figure B7 (Contd). Decision Tree for HMOR of table A7

```
chp = high and   cp = high and   rc = medium ==> class = medium
                                 rc = low ==> class = low
                                 rc = very_low ==> class = low
                                 rc = very_high ==> class = high
                                 rc = high ==> class = high

                 cp = medium and rc = medium ==> class = high
                                 rc = low ==> class = medium
                                 rc = very_low ==> class = medium
                                 rc = very_high ==> class = very_high
                                 rc = high ==> class = high

                 cp = low and    rc = medium ==> class = high
                                 rc = low ==> class = medium
                                 rc = very_low ==> class = medium
                                 rc = very_high ==> class = very_high
                                 rc = high ==> class = very_high

chp = medium and rc = medium and cp = high ==> class = medium
                                 cp = medium ==> class = medium
                                 cp = low ==> class = high

                 rc = low and    cp = high ==> class = low
                                 cp = medium ==> class = medium
                                 cp = low ==> class = medium

                 rc = very_low and cp = high ==> class = very_low
                                 cp = medium ==> class = low
                                 cp = low ==> class = low

                 rc = very_high and cp = high ==> class = high
                                 cp = medium ==> class = high
                                 cp = low ==> class = very_high

                 rc = high and   cp = high ==> class = high
                                 cp = medium ==> class = high
                                 cp = low ==> class = very_high

chp = low and    rc = medium ==> class = low
                 rc = low and    cp = high ==> class = very_low
                                 cp = medium ==> class = very_low
                                 cp = low ==> class = low

                 rc = very_low and cp = high ==> class = very_low
                                 cp = medium ==> class = very_low
                                 cp = low ==> class = low

                 rc = very_high and cp = high ==> class = low
                                 cp = medium ==> class = medium
                                 cp = low ==> class = medium

                 rc = high and   cp = high ==> class = low
                                 cp = medium ==> class = low
                                 cp = low ==> class = medium
```

Figure B8: Decision Tree for Slag Corrosion Resistance of table A8

rc = very_low and mp = high and gbd = very_high ==> class = medium
gbd = high ==> class = low
gbd = medium ==> class = low
gbd = low ==> class = low

mp = medium and gbd = very_high ==> class = low
gbd = high ==> class = very_low
gbd = medium ==> class = low
gbd = low ==> class = very_low

mp = low ==> class = very_low

rc = low and gbd = high and mp = high ==> class = medium
mp = medium ==> class = low
mp = low ==> class = low

gbd = medium and mp = high ==> class = medium
mp = medium ==> class = low
mp = low ==> class = low

gbd = low and mp = high ==> class = low
mp = medium ==> class = very_low
mp = low ==> class = very_low

rc = high and gbd = medium and mp = high ==> class = very_high
mp = medium ==> class = high
mp = low ==> class = medium

gbd = low and mp = high ==> class = high
mp = medium ==> class = high
mp = low ==> class = medium

gbd = very_low and mp = high ==> class = medium
mp = medium ==> class = medium
mp = low ==> class = low

rc = medium and gbd = medium and mp = high ==> class = high
mp = medium ==> class = high
mp = low ==> class = medium

gbd = low and mp = high ==> class = medium
mp = medium ==> class = low
mp = low ==> class = low

gbd = very_low and mp = high ==> class = medium
mp = medium ==> class = low
mp = low ==> class = low

rc = very_high and gbd = low and mp = high ==> class = very_high
mp = medium ==> class = very_high
mp = low ==> class = high

gbd = very_low and mp = high ==> class = very_high
mp = medium ==> class = high
mp = low ==> class = medium

Figure B9: Decision Tree for Oxidation Resistance of table A9

MEMBERSHIP FUNCTIONS FOR MODULE-1

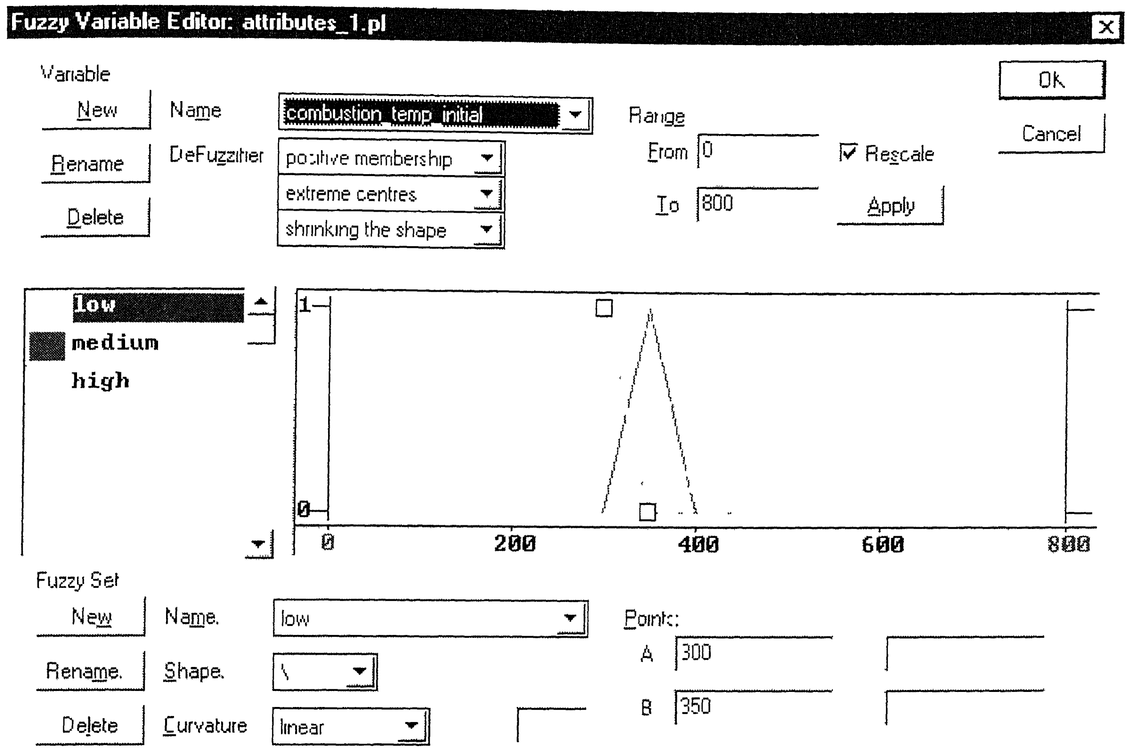


Figure C1: Membership function for Combustion Chamber Temperature

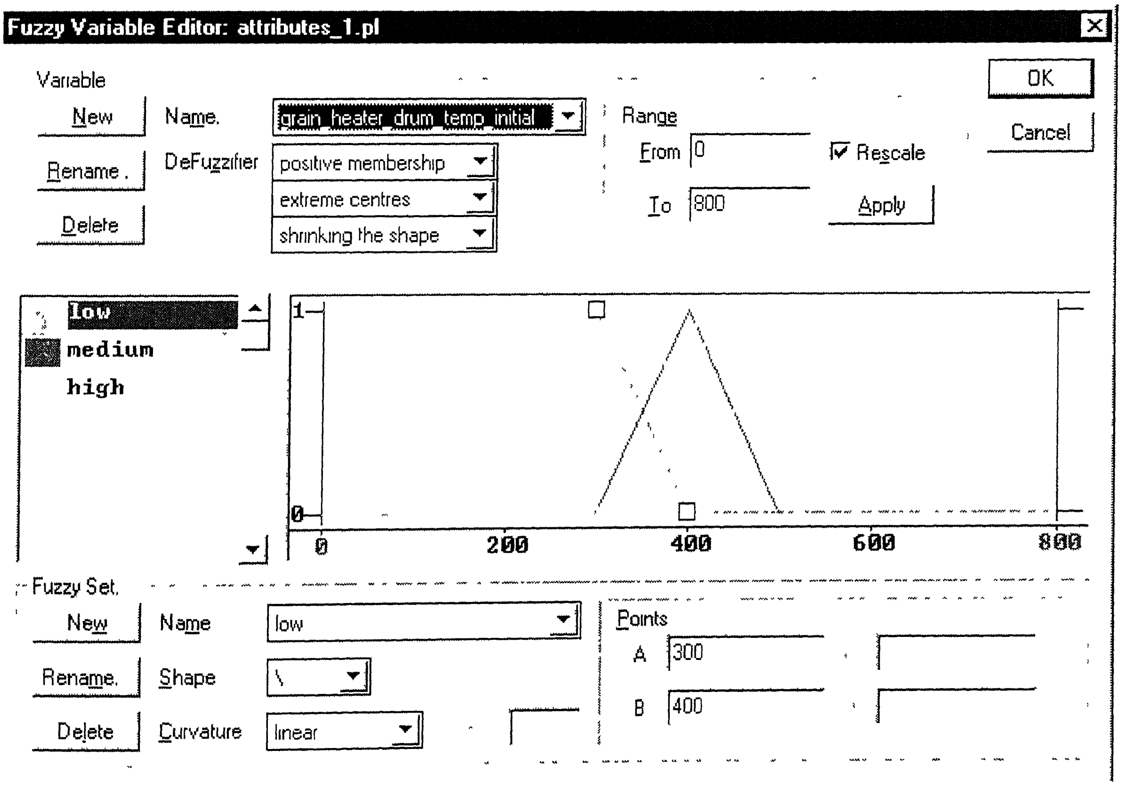


Figure C2: Membership function for Grain Heater Drum Temperature

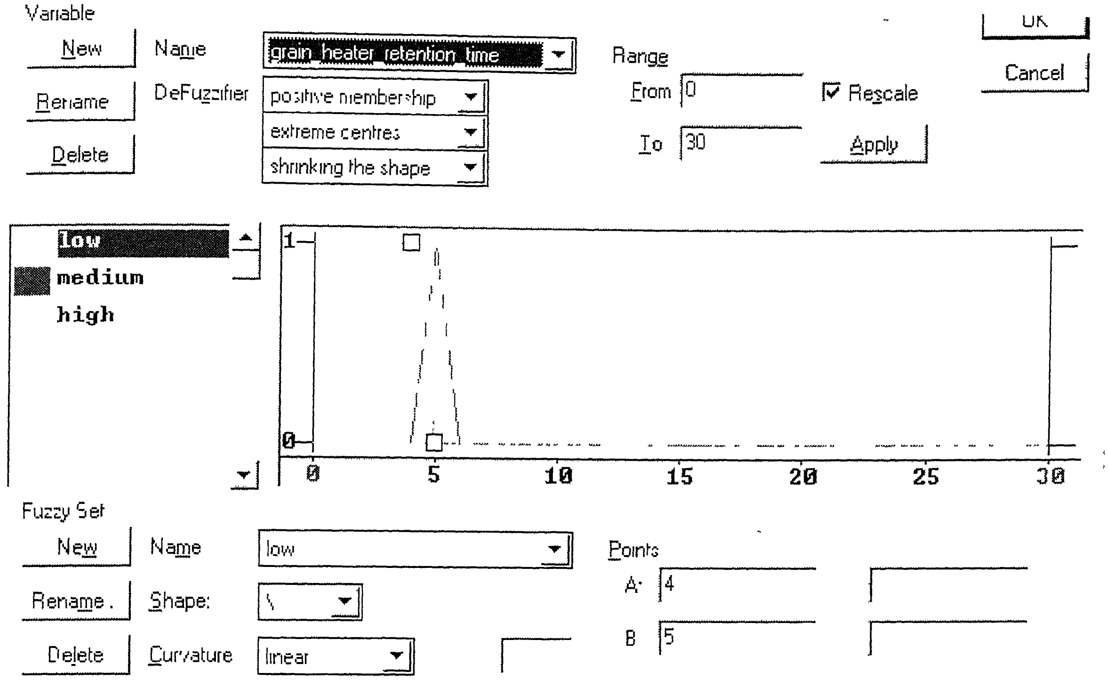


Figure C3: Membership function for Retention Time

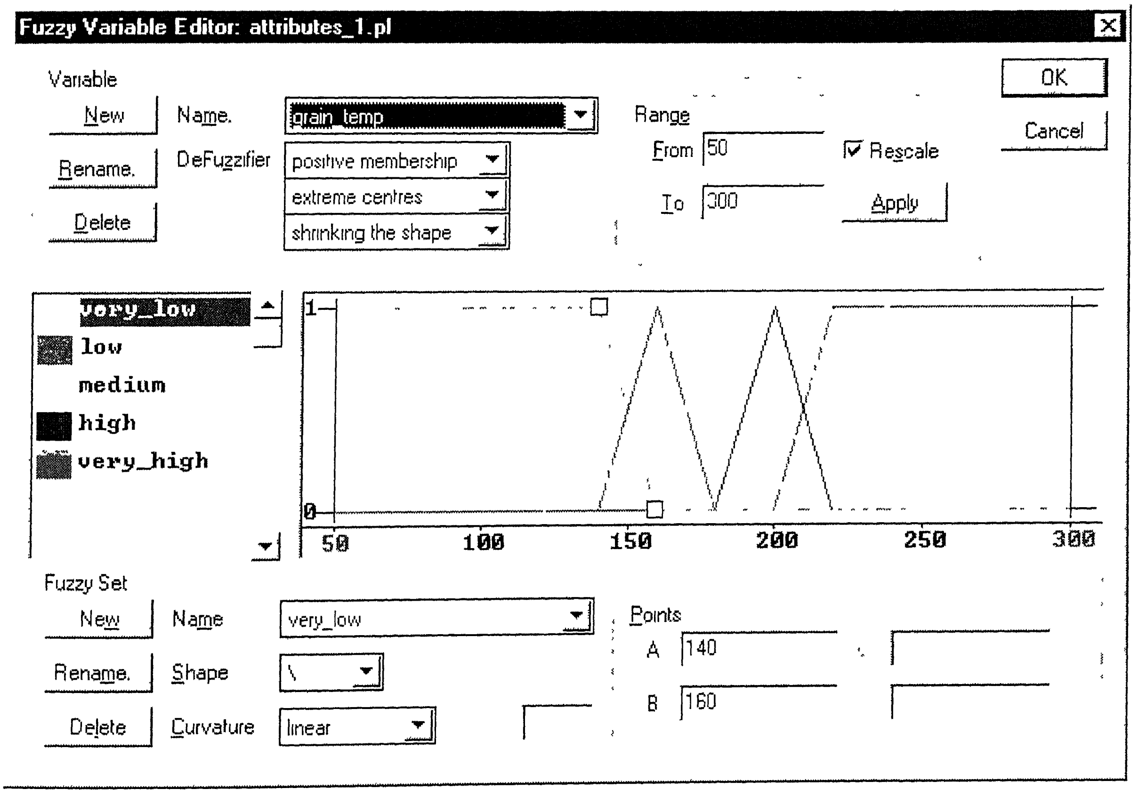


Figure C4: Membership function for Grain Temperature

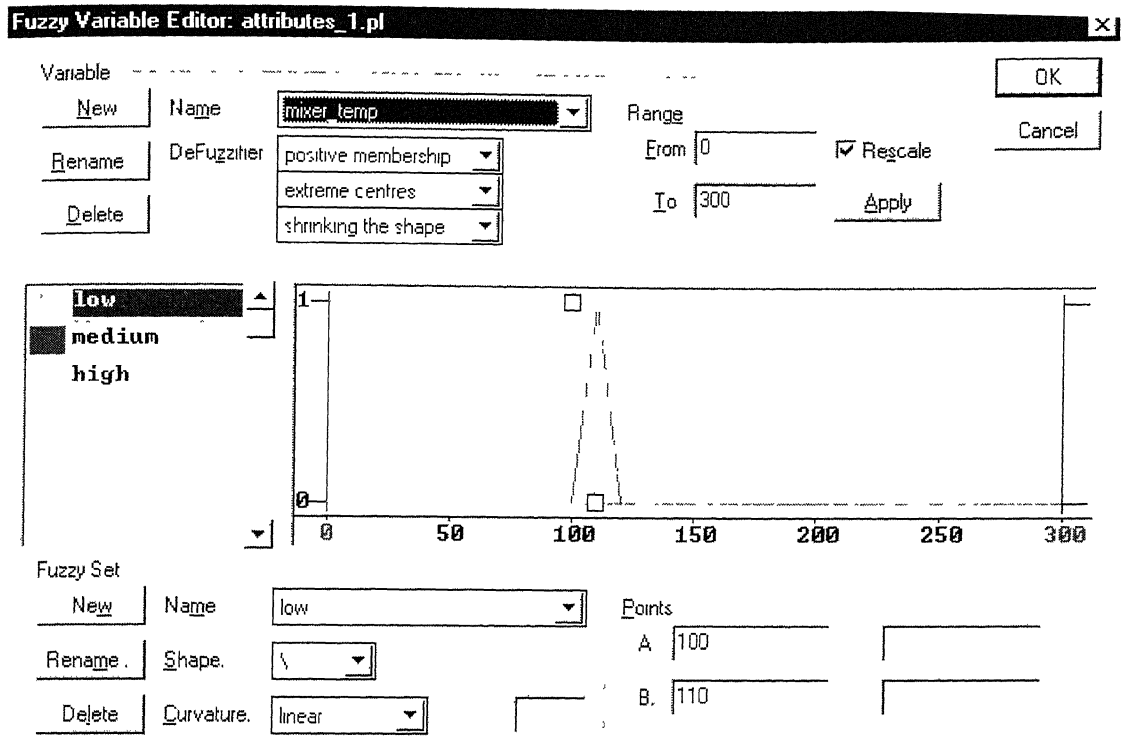


Figure C5: Membership function for Mixer Temperature

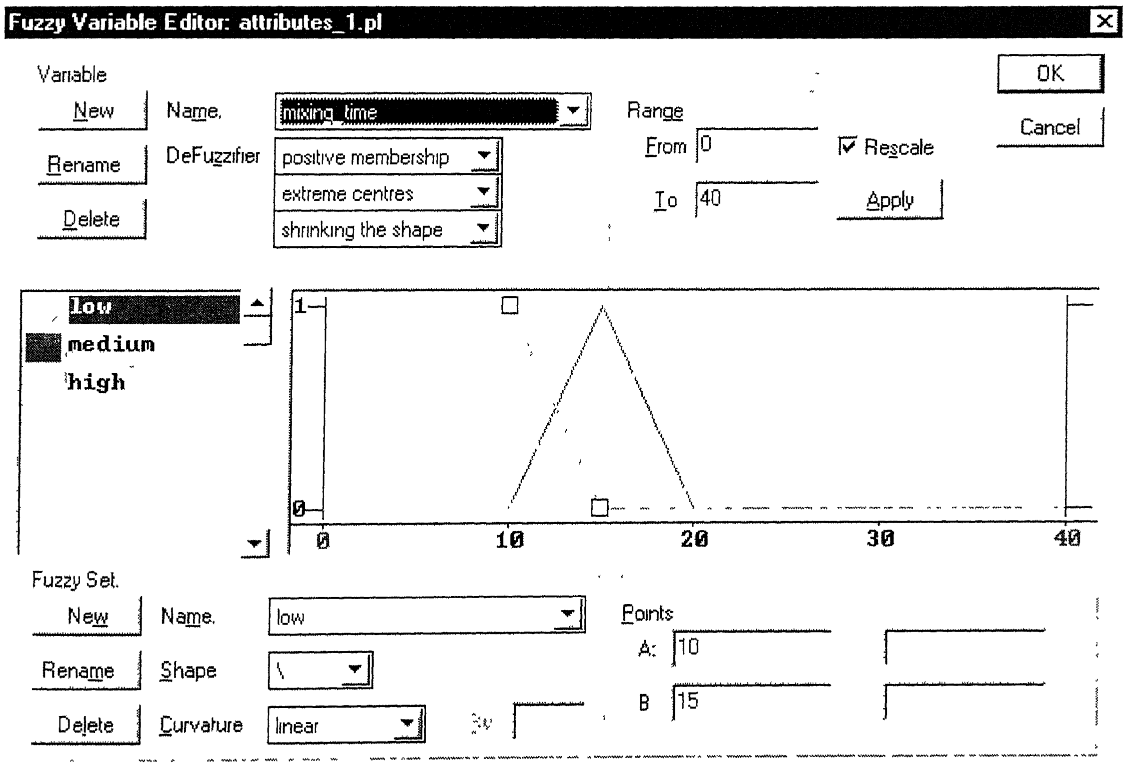


Figure C6: Membership function for Mixing Time

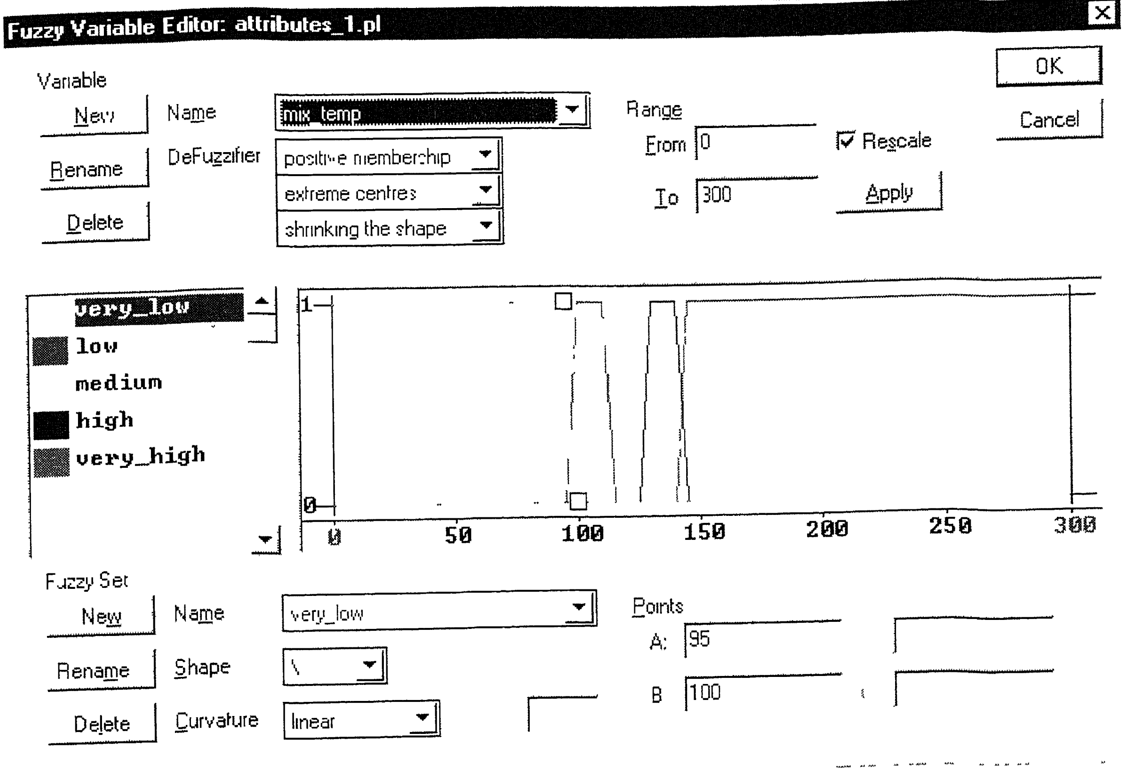


Figure C7. Membership function for Mix Temperature

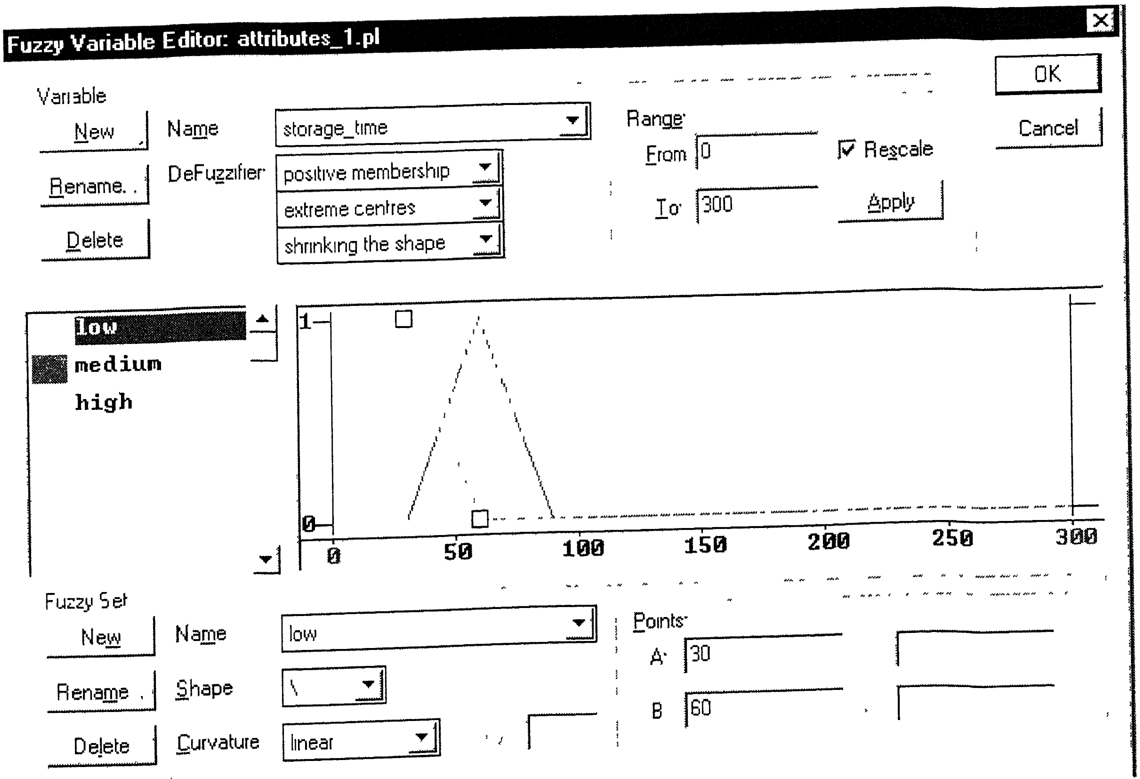


Figure C8: Membership function for Storage Time

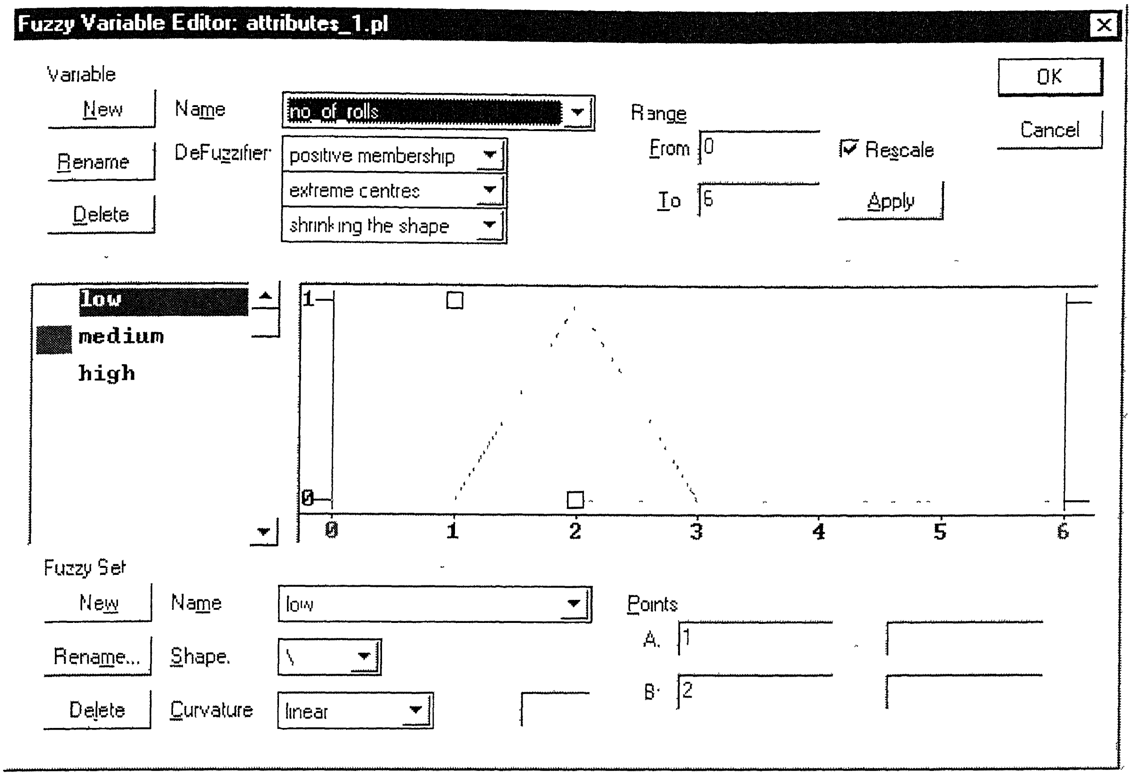


Figure C9: Membership function for Number of Rolls

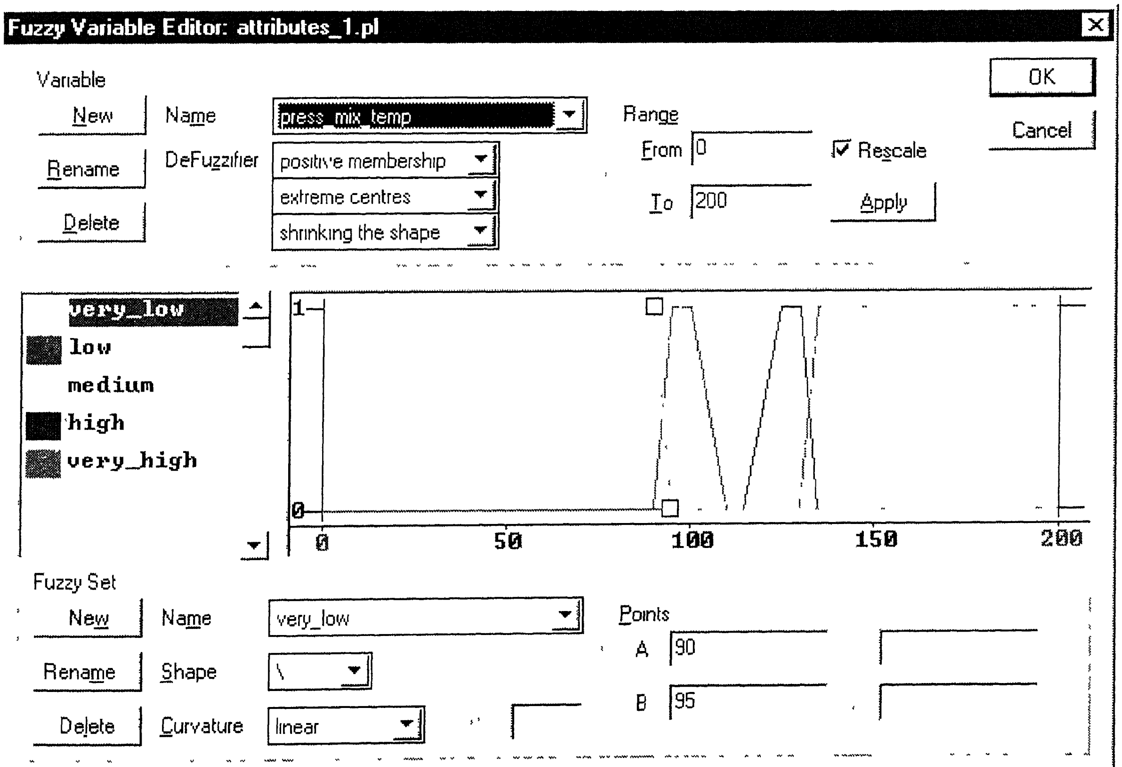


Figure C10: Membership function for Press Mix Temperature (1)

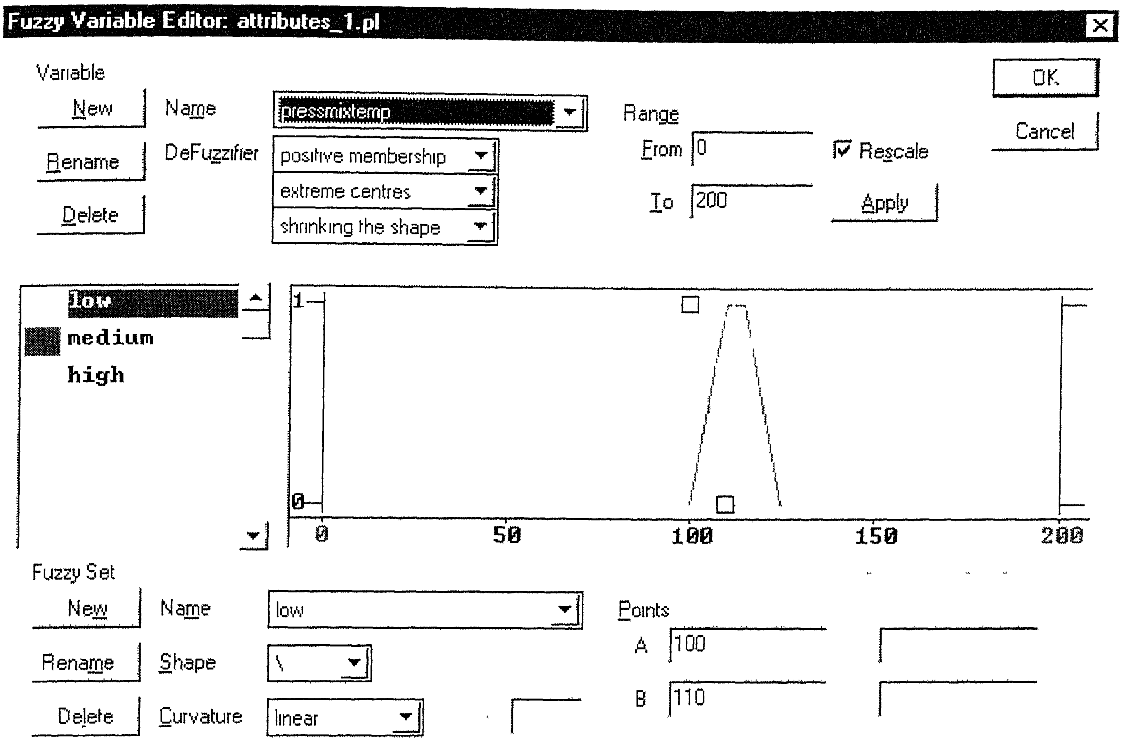


Figure C11: Membership function for Press Mix Temperature (2)

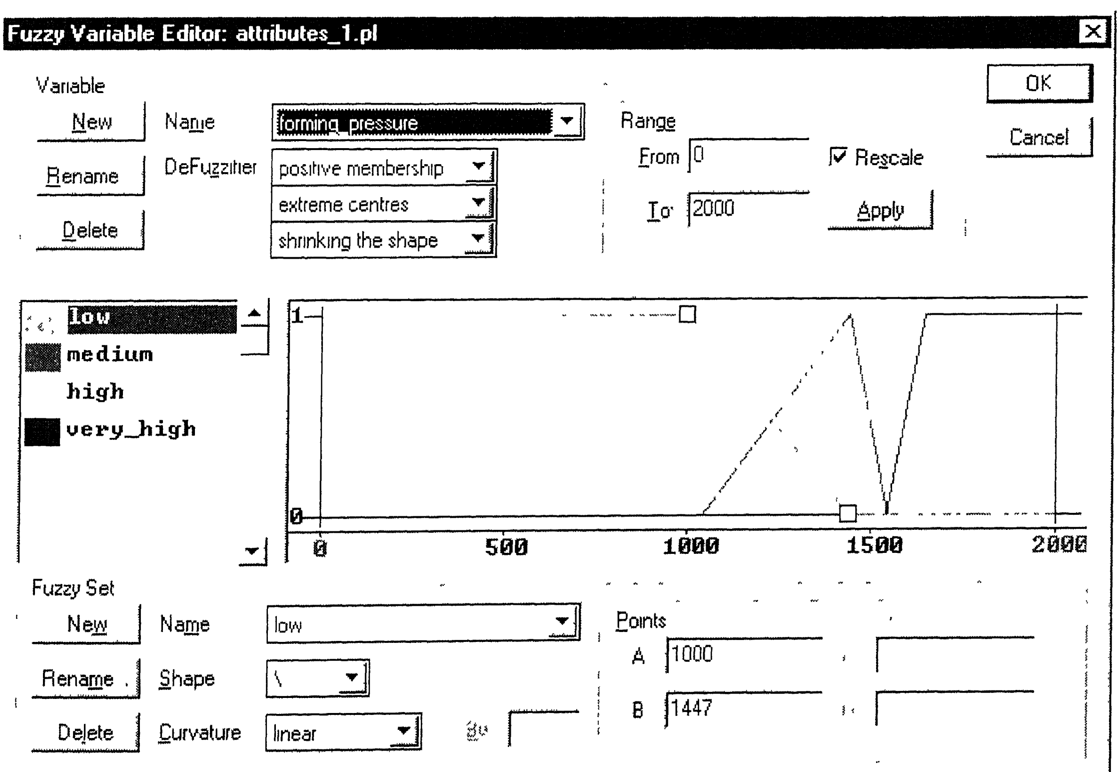


Figure C12. Membership function for Forming Pressure

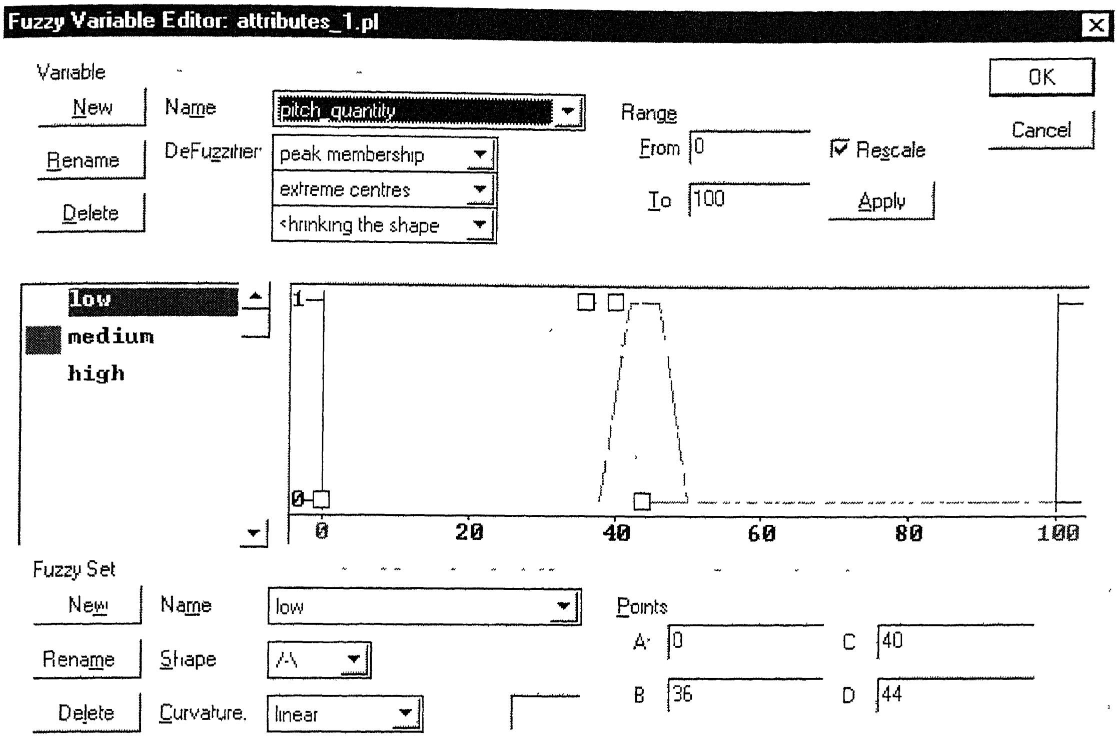


Figure C13: Membership function for Pitch Quantity

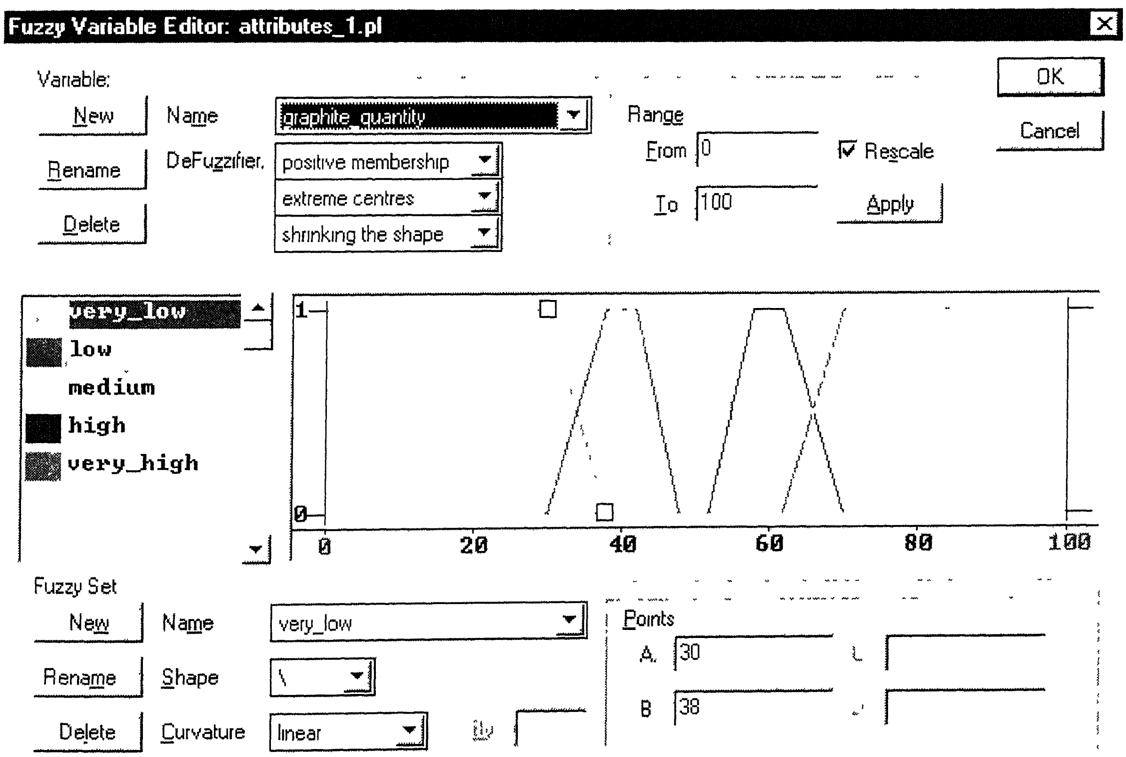


Figure C14: Membership function for Graphite Quantity

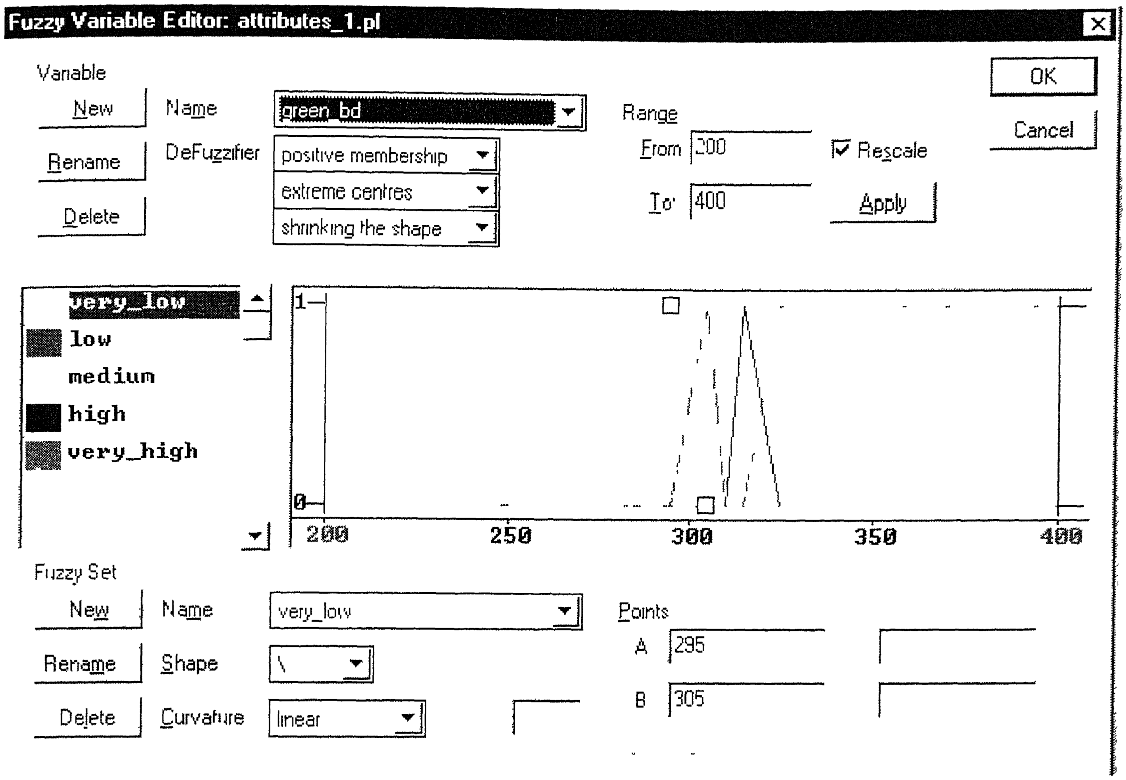


Figure C15: Membership function for Green Bulk Density

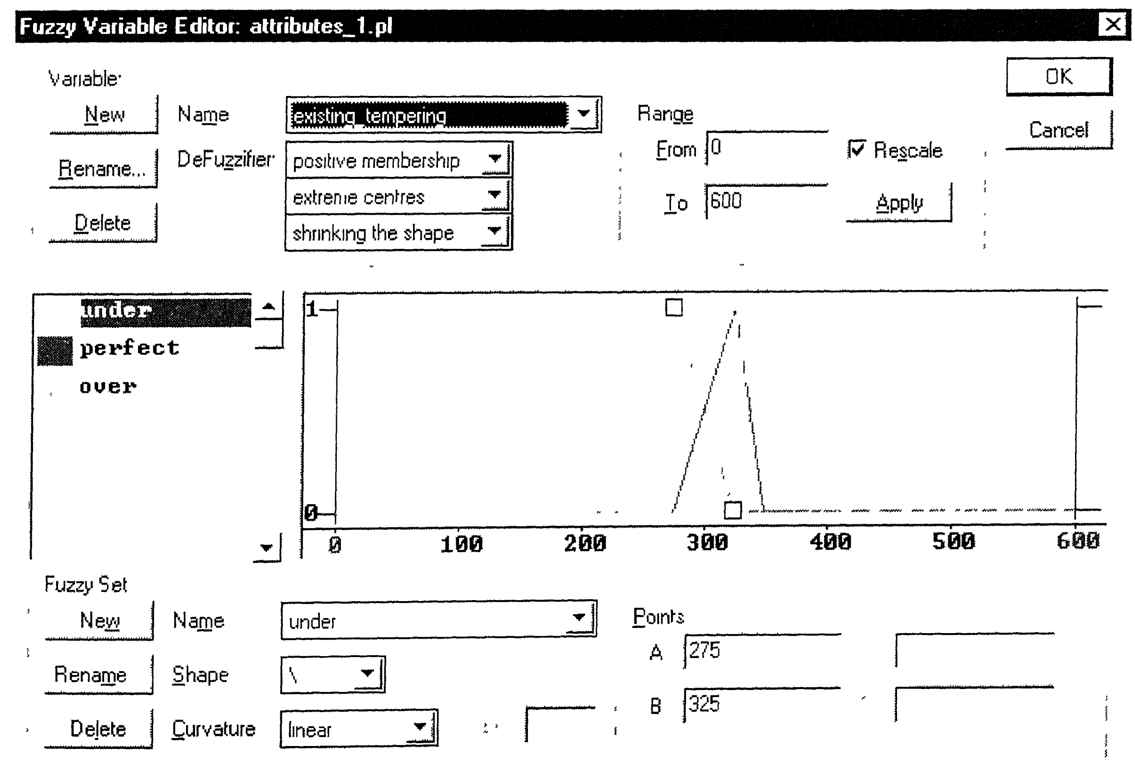


Figure C16: Membership function for Tempering Status

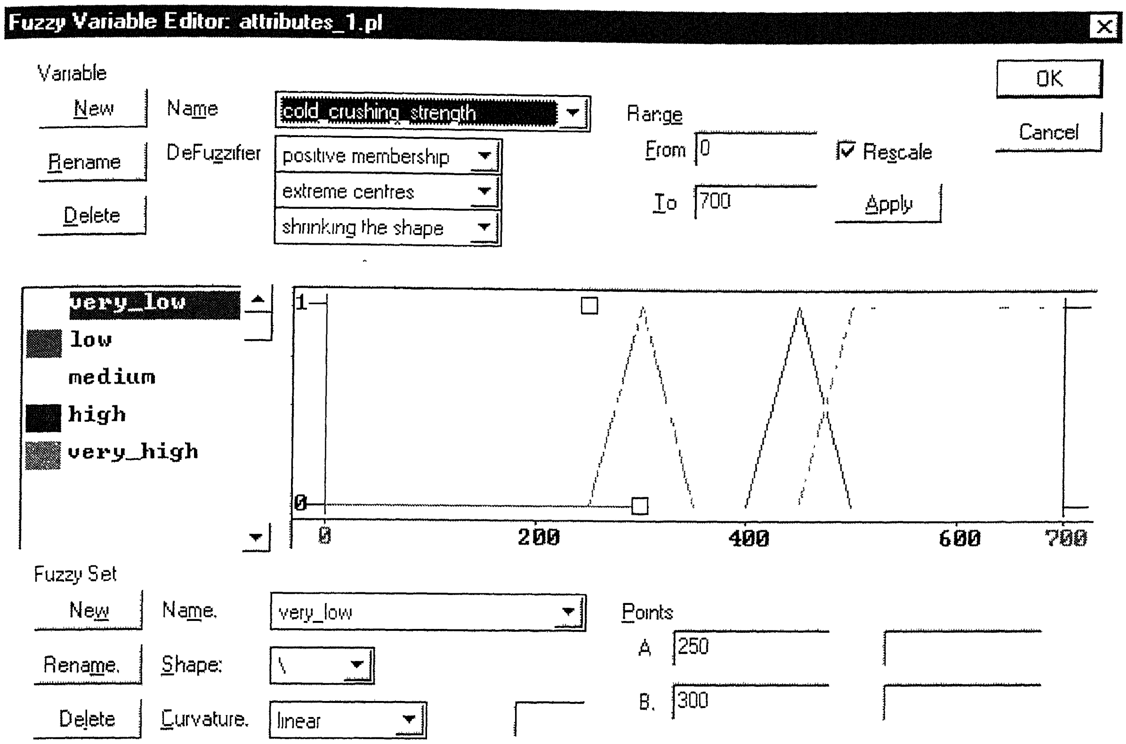


Figure C17: Membership function for Cold Crushing Strength

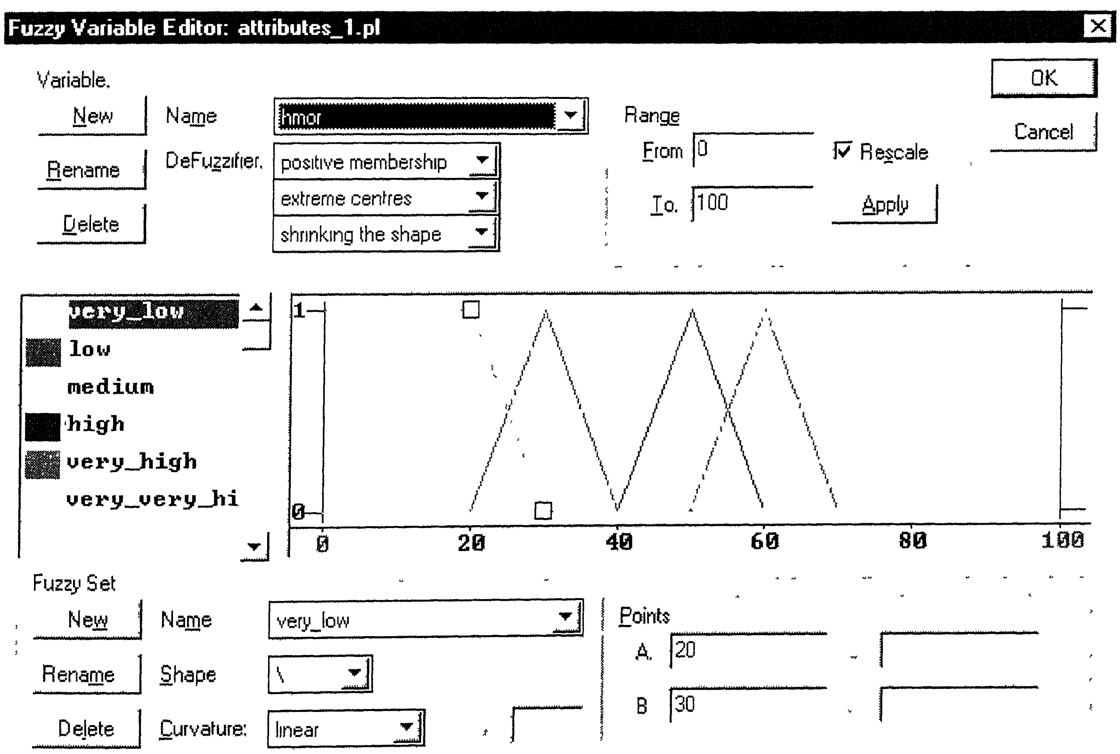


Figure C18: Membership function for High Modulus of Rupture

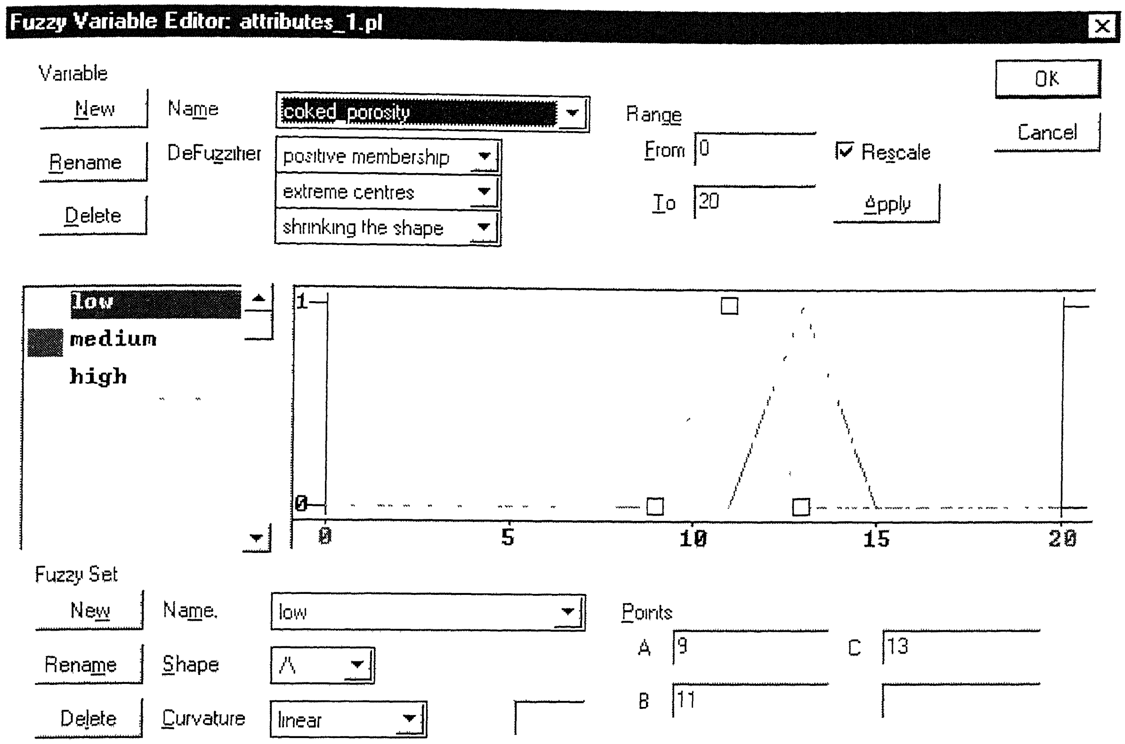


Figure C19: Membership function for Coked Porosity

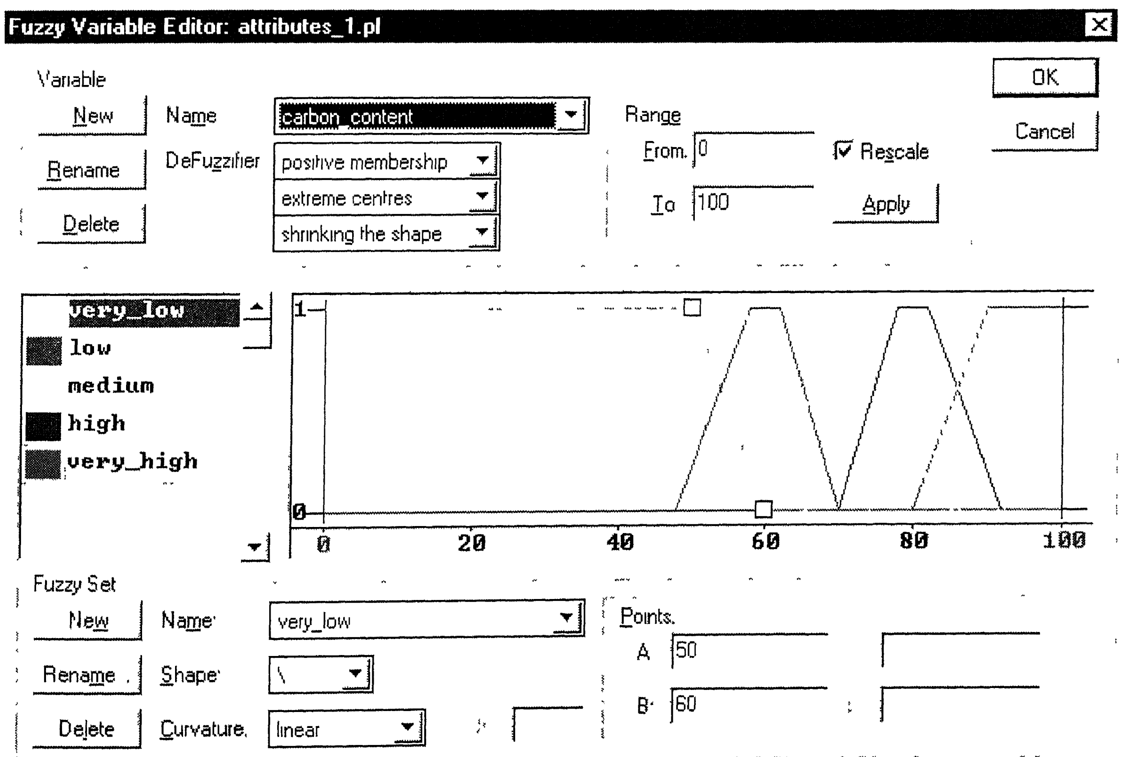


Figure C20: Membership function for Retained Carbon

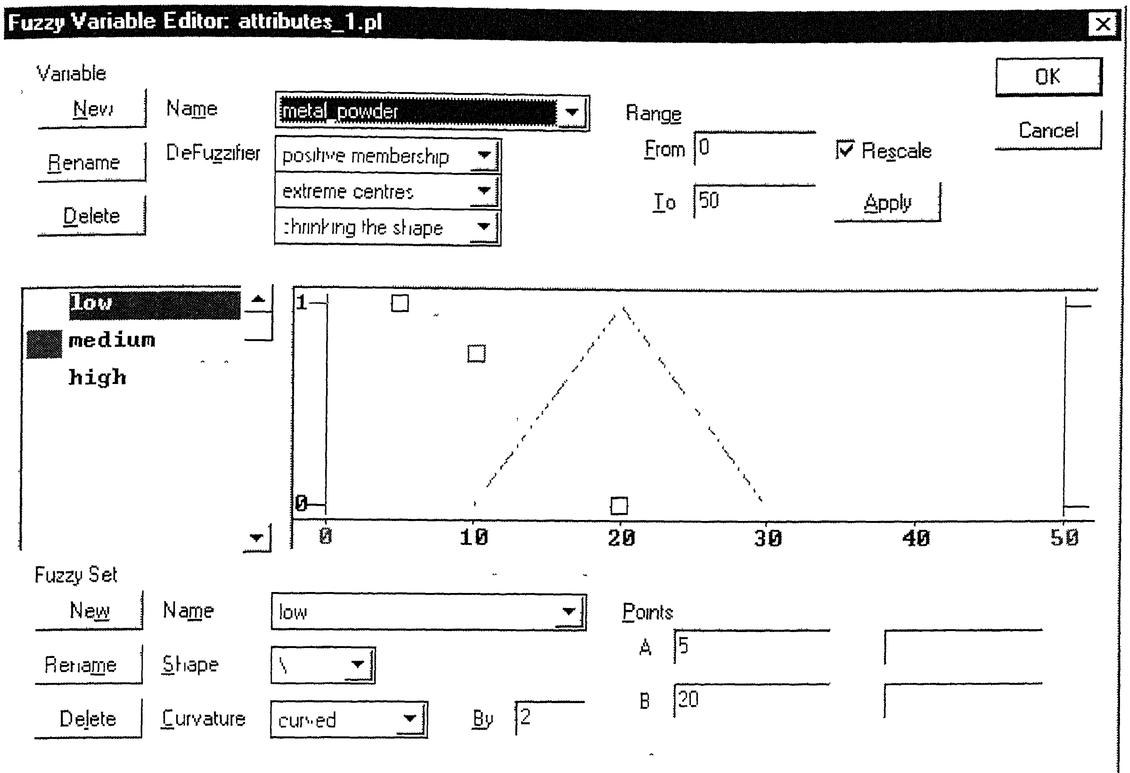


Figure C21: Membership function for Metal Powder

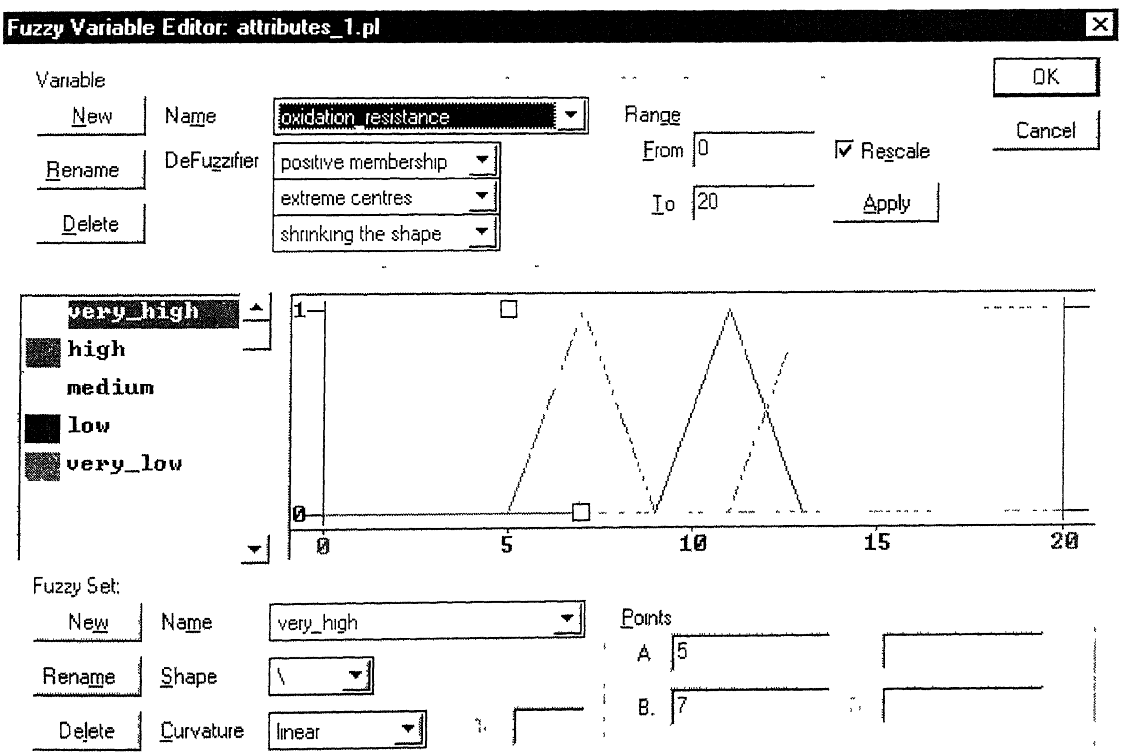


Figure C22: Membership function for Oxidation Resistance

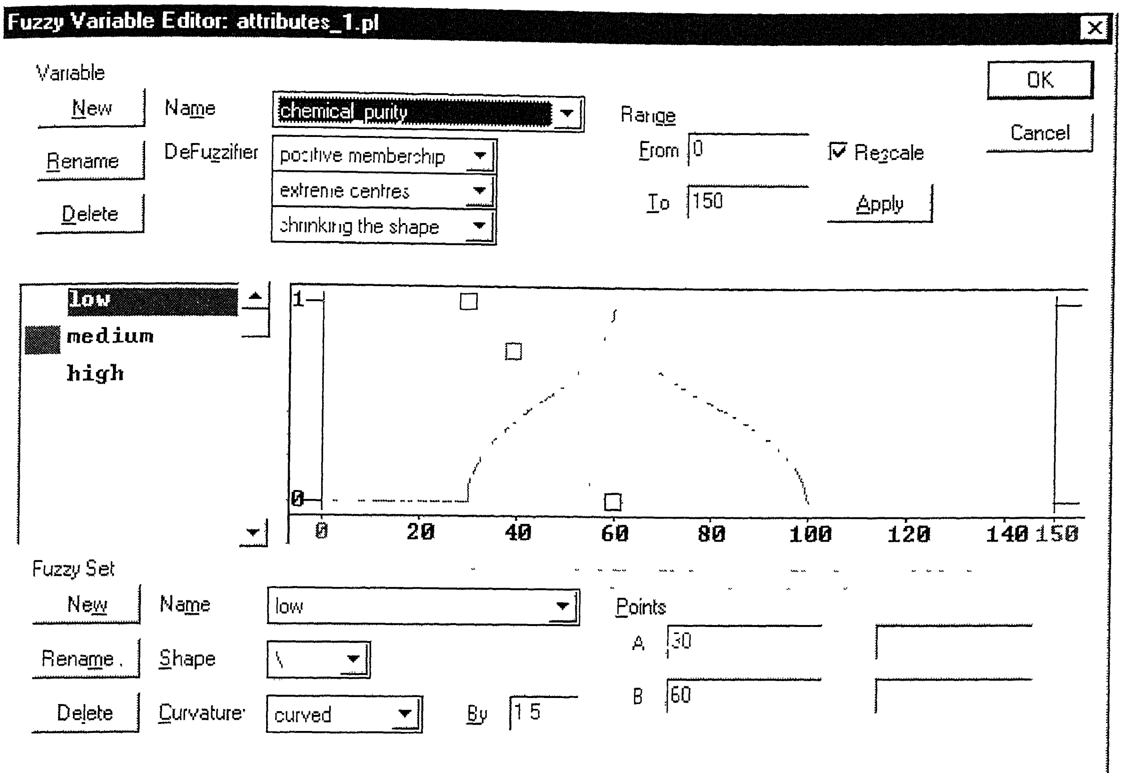


Figure C23. Membership function for Chemical Purity

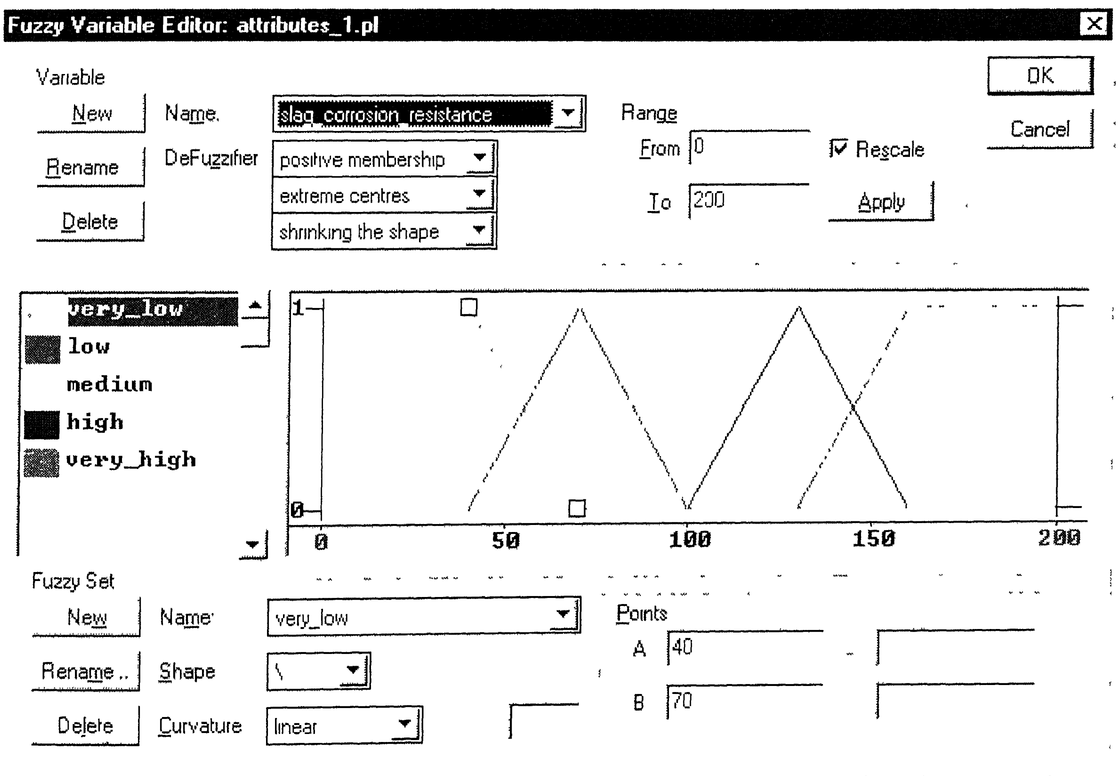


Figure C24: Membership function for Slag Corrosion Resistance

APPENDIX D

RESULTS OF MODULE-1

COMBUSTION CHAMBER TEMP (CCT)	GRAIN HEATER DRUM TEMP (GHDT)	RETENTION TIME (RT)	GRAIN TEMP (GT)
376 00	450 00	5 51	200 13
378 00	456 00	4 60	182 29
380 00	461 00	4 00	172 24
385 00	429 00	5 60	198 29
391 00	433 00	4 80	182 54
398 00	446 00	4 10	181 76
400 00	318 00	5 70	177 97
379 00	321 00	5 00	165 32
383 00	326 00	4 20	153 22
331 00	463 00	5 80	203 65
336 00	466 00	5 20	197 67
342 00	470 00	4 30	180 00
349 00	367 00	5 90	189 46
350 00	374 00	5 40	182 22
358 00	376 00	4 40	162 58
363 00	309 00	6 00	182 17
368 00	312 00	5 10	167 44
372 00	315 00	4 49	153 74
309 00	472 00	5 51	194 75
311 00	475 00	4 60	177 05
315 00	479 00	4 00	166 00
320 00	358 00	5 60	170 89
320 00	363 00	4 80	163 43
321 00	367 00	4 10	155 45
319 00	300 00	5 70	161 23
313 00	304 00	5 00	146 54
301 00	306 00	4 20	143.91

Table D1: Results for Grain Temperature

GRAIN TEMP (GT)	MIXER TEMP (MT)	MIXING TIME (TM)	MIX TEMP (MIX)
211 00	115 10	17 51	137 71
214 00	116 00	12 80	138 84
216 00	117 00	10 00	140 38
218 00	106 00	18 00	141 67
213 00	108 00	13 00	133 67
214 00	109 00	10 50	136 32
216 00	100 00	18 50	140 38
218 00	101 00	14 00	137 50
212 00	102 00	11 00	130 00
191 00	118 00	19 00	128 25
194 00	119 00	15 00	130 50
198 00	120 00	11 50	133 13
200 00	112 00	19 50	135 00
202 00	114 00	16 00	135 53
204 00	111 00	12 00	136 00
207 00	103 00	20 00	136 52
209 00	104 00	17 00	137 14
201 00	103 00	12 40	127 49
172 00	115 10	17 51	113 39
175 00	116 00	12 80	115 37
177 00	117 00	10 00	117 35
179 00	106 00	18 00	114 00
183 00	108 00	13 00	119 21
186 00	109 00	10.50	122 73
188 00	100.00	18 50	117 00
189 00	101.00	14 00	118 75
180 00	102.00	11 00	117 00
151 00	118 00	19 00	113 25
153 00	119 00	15 00	105 00
156 00	120 00	11 50	104 13
159 00	112 00	19 50	108 00
160 00	114 00	16 00	108 75
162 00	111 00	12 00	107 14
165 00	103 00	20 00	108 95
169.00	104 00	17 00	111 32
163 00	103 00	12 40	108 36
140 00	115 10	17 51	105 00
141 00	116 00	12 80	102 92
143 00	117 00	10 00	98 91
144 00	106 00	18 00	103 18
146 00	108 00	13.00	103.18
147 00	109 00	10 50	101 18
148 00	100 00	18 50	101.67
149 00	101 00	14.00	102.11
142 00	102 00	11 00	99 29

Table D2: Results for Mix Temperature

MIX TEMP (MIX)	STORAGE TIME (ST)	NUMBER OF ROLLS (ROLL)	PRESS MIX TEMP (PMT)
142 60	76 00	3 00	106 04
143 00	79 00	2 00	112 50
144 00	82 00	0 00	126 12
145 00	46 00	3 00	105 86
150 00	51 00	2 00	116 08
143 00	58 00	0 00	126 50
144 00	30 00	3 00	112 50
145 00	32 00	2 00	125 05
150 00	35 00	0 00	132 04
128 00	83 00	3 00	107 64
133 00	86 00	2 00	112 50
141 00	89 00	0 00	126 12
142 00	63 00	3 00	107 64
129 00	67 00	2 00	110 07
133 00	70 00	0 00	126 12
141 00	37 00	3 00	110 07
142 00	39 00	2 00	121 01
129 00	42 00	0 00	122 23
113 00	76 00	3 00	98 88
114 00	79 00	2 00	98 88
123 00	82 00	0 00	112 50
126 00	46 00	3 00	103 11
127 00	51 00	2 00	109 54
114 00	58 00	0 00	110 15
123 00	30 00	3.00	98 88
126.00	32 00	2 00	104 93
127 00	35 00	0 00	117 36
98 00	83 00	3 00	97 01
99 00	86 00	2 00	98 07
102 00	89 00	0 00	98 88
111 00	63 00	3 00	98 88
112 00	67 00	2 00	98 88
99 00	70 00	0 00	97.93
102 00	37 00	3 00	98 88
111 00	39 00	2 00	98 88
112 00	42 00	0 00	104.93
93 00	76 00	3 00	90 00
95 00	79 00	2 00	90 00
96 00	82 00	0 00	94 23
97 00	46.00	3 00	95 79
97 40	51 00	2 00	96 19
95 00	58 00	0 00	98 88
96 00	30 00	3.00	93 41
97 00	32 00	2 00	95 55
97 40	35 00	0 00	98 88

Table D3: Results for Press Mix Temperature

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
1501 00	132 60	4 73	6 70	3 01
1510 00	133 00	4 74	5 60	3 06
1520 00	134 00	4 75	4 60	3 13
1530 00	135 00	4 76	3 50	3 20
1540 00	138 00	4 77	3 00	3 25
1550 00	133 50	4 16	6 80	2 99
1560.00	118 00	4 18	5 70	3 04
1570 00	120 00	4 20	4 70	3 12
1580 00	122 00	4 61	3 70	3 17
1590 00	128 00	4 63	3 10	3 24
1501 00	131 00	3 50	6 90	2 96
1510 00	132 00	3 80	5 80	3 04
1520 00	122 00	4 09	5.20	3 07
1530 00	128 00	4 06	4 20	3 14
1540 00	131 00	4 00	3 20	3 19
1550 00	105 50	4 73	7 00	2 99
1560 00	107 00	4 74	6 30	3 02
1570 00	109 00	4 75	5 30	3 02
1580 00	112 00	4 76	4 40	3 14
1590 00	116 00	4 77	3 30	3 16
1501.00	118 00	4 16	6 70	2 98
1510 00	105 50	4 18	5 60	3 01
1520 00	107 00	4 20	4 60	3 07
1530 00	109 00	4 61	3 50	3 14
1540 00	112 00	4 63	3 00	3 16
1550 00	116 00	3 50	6 80	2 97
1560 00	118 00	3 80	5 70	3 04
1570 00	107 00	4 09	4.70	3 07
1580 00	109 00	4 06	3 70	3.11
1590 00	112 00	4 00	3 10	3 16
1501.00	93 00	4 73	6 90	2.96
1510 00	94 00	4 74	5 80	3 00
1520 00	97 00	4 75	5 20	3 06
1530 00	101 00	4 76	4 20	3.11

Table D4: Results for Green Bulk Density (Contd…)

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
1540 00	103 00	4 77	3 20	3 14
1550 00	104 00	4 16	7 00	2 95
1560 00	88 00	4 18	6 30	3 02
1570 00	92 00	4 20	5 30	3 07
1580 00	91 00	4 61	4 40	3 07
1590 00	92 40	4 63	3 30	3 14
1520 00	91 40	3 50	6 70	2 98
1530 00	90 50	3 80	5 60	3 01
1540 00	104 00	4 09	4 60	3 06
1550 00	88 00	4 06	3 50	3 13
1560 00	92 00	4 00	3 00	3 13
1480 00	132 60	4 73	6 80	3.00
1225 00	133 00	4 74	5 70	3 00
1250 00	134 00	4 75	4 70	3 08
1275 00	135 00	4 76	3 70	3 16
1300 00	138 00	4 77	3 10	3 22
1325 00	133 50	4 16	6 90	2 96
1350 00	118 00	4 18	5 80	2 95
1375 00	120 00	4 20	5 20	3 06
1400 00	122 00	4 61	4 20	3 15
1450 00	128 00	4 63	3 20	3 23
1480 00	131 00	3 50	7 00	2 95
1225 00	132 00	3 80	6 30	2 98
1250 00	122 00	4 09	5 30	3 04
1275 00	128 00	4 06	4 40	3 11
1300 00	131 00	4 00	3 30	3 16
1325 00	105 50	4 73	6 70	2 98
1350 00	107 00	4 74	5 60	3 02
1375 00	109 00	4.75	4 60	3 11
1400 00	112 00	4 76	3 50	3 14
1450 00	116.00	4 77	3 00	3 18
1480.00	118 00	4 16	6 80	2 97
1225 00	105 50	4 18	5 70	2 99
1250 00	107 00	4 20	4 70	3 03

Table D4 (Contd.): Results for Green Bulk Density (Contd...)

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
1275 00	109 00	4 61	3 70	3 13
1300 00	112 00	4 63	3 10	3 15
1325 00	116 00	3 50	6 90	2 96
1350 00	118 00	3.80	5 80	3 01
1375 00	107 00	4 09	5 20	3 04
1400 00	109 00	4 06	4 20	3 09
1450 00	112 00	4 00	3 20	3 13
1480 00	93 00	4 73	7 00	2 95
1225 00	94 00	4 74	6 30	2 95
1250 00	97 00	4 75	5 30	3 01
1275 00	101 00	4 76	4 40	3 08
1300 00	103 00	4 77	3 30	3 10
1325 00	104 00	4 16	6 70	2 98
1350 00	88 00	4 18	5 60	2 97
1375 00	92 00	4 20	4 60	3 03
1400 00	91 00	4 61	3 50	3 09
1450 00	92 40	4 63	3 00	3 10
1275 00	91 40	3 50	6 80	2 95
1300 00	90 50	3 80	5 70	2 96
1325 00	104 00	4 09	4 70	3 02
1350 00	88 00	4 06	3 70	3 06
1375 00	92 00	4 00	3 10	3 09
1005 00	132 60	4 73	6 90	2 96
1025 00	133 00	4 74	5 80	2 99
1050 00	134 00	4 75	5 20	3 07
1075 00	135 00	4 76	4 20	3 11
1100.00	138 00	4 77	3 20	3 17
1125 00	133.50	4 16	7 00	2 95
1150 00	118 00	4 18	6 30	2 97
1200 00	120 00	4 20	5 30	3 03
1225 00	122 00	4 61	4.40	3 11
1249 00	128 00	4 63	3 30	3 19
1005 00	131 00	3 50	6 70	2 95
1025 00	132 00	3 80	5 60	2 97

Table D4 (Contd.)· Results for Green Bulk Density (Contd ..)

FORMING PRESSURE (FP)	PRESS MIX TEMP (PMT)	PITCH QUANTITY (PQ)	GRAPHITE QUANTITY (GQ)	GREEN BULK DENSITY (GBD)
1050 00	122.00	4 09	4.60	3 05
1075 00	128 00	4 06	3.50	3 10
1100 00	131.00	4 00	3.00	3 15
1125 00	105 50	4 73	6.80	2 97
1150 00	107.00	4 74	5.70	2 99
1200 00	109 00	4 75	4 70	3 08
1225 00	112 00	4 76	3 70	3 14
1249 00	116 00	4 77	3.10	3 16
1005 00	118 00	4 16	6.90	2 95
1025 00	105 50	4 18	5.80	2 95
1050 00	107 00	4 20	5.20	3 00
1075 00	109 00	4 61	4.20	3 12
1100 00	112 00	4 63	3.20	3 13
1125 00	116 00	3 50	7 00	2 95
1150 00	118 00	3 80	6.30	2 97
1200 00	107 00	4 09	5.30	3 02
1225 00	109 00	4 06	4.40	3 05
1249.00	112 00	4 00	3 30	3.14
1005 00	93 00	4 73	6.70	2 95
1025 00	94 00	4 74	5.60	2 97
1050 00	97 00	4.75	4.60	3 05
1075 00	101 00	4 76	3.50	3 07
1100 00	103.00	4 77	3.00	3 13
1125 00	104 00	4 16	6.80	2 97
1150 00	88.00	4 18	5 70	2 96
1200 00	92 00	4 20	4.70	3 00
1225 00	91 00	4 61	3.70	3 06
1249 00	92.40	4 63	3.10	3 08
1005 00	91 40	3 50	6.90	2 95
1025 00	90 50	3 80	5.80	2 95
1050 00	104 00	4 09	5.20	2.99
1075 00	88 00	4.06	4.20	3 06
1100.00	92 00	4 00	3 20	3.07
1025 00	132 00	3 80	5.60	2 97
1050 00	122 00	4 09	4.60	3 05

Table D4 (Contd.): Results for Green Bulk Density

PITCH QUANTITY (PQ)	GREEN BULK DENSITY (GBD)	COKED POROSITY (CP)
4 75	3 25	12 17
4 60	3 23	12 20
3 80	3 21	11 00
4 80	3 19	13 27
4 10	3 15	12 00
4 00	3 13	11 91
4 70	3 11	14 00
4 40	3 09	13 00
3 40	3 08	13 00
4 72	3 07	14 00
4 65	3 05	13 83
4 05	2 98	14 40
5 00	2 97	15 00
4 40	2 95	15 00
3 60	2 94	15 00
4.72	3 21	12 75
4 63	3 23	12 24
4 20	3 25	11 00
4 79	3 13	14 00
4 16	3 15	12 20
4 02	3 17	11 84
4 80	3 08	14 02
4 40	3 10	13 00
3.80	3 13	11 88
4 73	2 98	14 48
4 19	3.00	14 00
3.50	3 09	13 00
5.00	2 97	15 00
4 40	2.95	15 00
3.90	2 80	15 00

Table D5: Results for Coked Porosity

GREEN BULK DENSITY (GBD)	PITCH QUANTITY (PQ)	TEMPERING STATUS (TS)	COLD CRUSHING STRENGTH (CCS)
3 21	4 71	302 00	431 67
3 23	4 72	275 00	455 26
3 25	4 73	338 00	474 00
3 21	4 11	308 00	435 00
3 23	4 13	280 00	407 22
3 25	4 15	340 00	475 00
3 21	3 80	312 00	407 14
3 23	4 09	285 00	407 07
3 25	4 06	342 00	475 56
3 13	4.74	314 00	427 00
3 15	4 75	290 00	415 00
3 17	4 76	344 00	414 55
3 13	4 61	318 00	427 00
3 15	4 63	295 00	417 82
3 17	4 65	347 00	402 32
3 13	4 06	321 00	376 47
3 15	4 00	277 00	376 53
3 17	4 09	349 00	399 00
3 08	4 77	325 00	400 00
3 10	4 78	282 00	407 91
3 13	4 79	344 00	392 03
3 08	4 15	328 00	342 86
3 10	4 16	286 00	365 73
3 13	4 18	339 00	375 00
3 08	3 30	330 00	286 11
3 10	3 40	289 00	362 79
3 13	3 50	345 00	353 85
2 98	4 77	334 00	304 93
3 00	4.78	292 00	331 52
3 09	4 79	344 00	365 13
2.98	4 63	327 00	301 49
3 00	4.65	294 00	329.79
3 09	4 69	340 00	368 18
2.98	3 80	319 00	263 00
3 00	4 09	297 00	325 00
3 09	4 06	338 00	332 02
2.97	4 74	320 00	298 51
2.95	4 75	299 00	276 00
2.80	4 76	341 00	250 00
2.97	4.13	306.00	303 38
2 95	4.15	296 00	275.00
2 80	4 16	346 00	250 00
2.97	3 30	311 00	262.50
2.95	3 40	283 00	250 00
2 80	3 50	344 00	250.00

Table D6: Results for Cold Crushing Strength

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
8 70	2 98	2 70	426 00	61 67
8 80	2 99	3 00	328 00	64 17
8 90	3 03	3 20	277 00	66 43
9 00	3 05	1 30	430 00	55 28
8 70	3 07	2 00	330 00	61 33
8 80	2 99	2 20	280 00	51 08
8.90	3 03	0 00	440 00	48 00
9 00	3 05	0 50	340 00	48 00
8 70	3 07	1 00	290 00	40 00
8 80	2 95	2 70	450 00	63 33
8 90	2 96	3.00	424 00	64 80
9 00	2 97	3 20	300 00	62 00
8 70	2 97	1 30	460 00	50 14
8.80	2 98	2 00	410 00	56 00
8 90	2 95	2 20	310 00	48 14
9 00	2 96	0 00	470 00	41 43
8 80	2 97	0 50	420 00	42 50
8 90	2.97	1 00	320 00	42 00
7 70	3 08	2.70	426 00	65 81
7 80	3 09	3 00	328 00	67 37
8 30	3.10	3 20	277 00	70 00
8 40	3 11	1 30	430 00	51 76
7 70	3 12	2 00	330 00	61 64
7 80	3 09	2 20	280 00	58 17
8.30	3 10	0 00	440 00	48 00
8 40	3 11	0 50	340 00	40 00
7.70	3 12	1.00	290 00	36 15
7 80	2 98	2 70	450 00	56 58
8.30	2.99	3 00	424 00	64 35
8.40	3 03	3 20	300 00	63 33
7 70	3.05	1 30	460 00	49 32
7 80	3 07	2 00	410 00	64 00
8.30	2.99	2 20	310 00	50 67

Table D7: Results for High Modulus of Rupture (Contd…)

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
8 40	3 03	0 00	470 00	47 50
7 70	3 05	0 50	420 00	44 00
7 80	3 07	1 00	320 00	37 06
8 30	2 95	2 70	426 00	60 00
8 40	2 96	3 00	328 00	61 52
7 70	2 97	3 20	277 00	51 80
7 80	2 97	1 30	430 00	38 92
8 30	2 98	2 00	330 00	52 33
8 40	2 95	2 20	280 00	45 19
7 70	2 96	0 00	440 00	35 42
7 80	2 97	0 50	340 00	34 40
8 30	2 97	1 00	290 00	40 00
6 60	3 09	2 70	450 00	62 90
6 70	3 10	3 00	424 00	65 81
7.30	3 11	3 20	300 00	70 00
7 00	3 12	1 30	460 00	52 24
6 60	3 09	2 00	410 00	57 93
6 70	3 10	2 20	310 00	53 33
7 30	3 11	0 00	470 00	43 85
7 00	3.12	0 50	420 00	40 00
6 60	3 10	1 00	320 00	34 00
6 70	2 98	2 70	426 00	48 35
7 30	2 99	3 00	328 00	54 42
7.00	3.03	3 20	277 00	54 59
6 60	3 05	1 30	430 00	38 21
6.70	3.07	2 00	330 00	51 64
7 30	2.99	2 20	280 00	39 73
7 00	3 03	0 00	440 00	35 00
6 60	3 05	0 50	340 00	31 72
6.70	3.07	1 00	290 00	26 15
7 30	2 95	2 70	450 00	50 50
7 00	2 96	3 00	424 00	46 18
6 60	2.97	3 20	300 00	45 22
6.70	2.97	1 30	460 00	40 14
7.30	2.98	2 00	410.00	46 36

Table D7 (Contd.): Results for High Modulus of Rupture (Contd…)

RETAINED CARBON (RC)	GREEN BULK DENSITY (GBD)	METAL POWDER (MP)	COLD CRUSHING STRENGTH (CCS)	HIGH MODULUS OF RUPTURE (HMOR)
7 00	2 95	2 20	310 00	32 00
6 70	2 96	0 00	470 00	31 43
7 30	2 97	0 50	420 00	31 11
7 00	2 97	1 00	320 00	25 00
5 50	3 13	2 70	426 00	56 34
5 70	3 13	3 00	328 00	55 60
6 00	3 14	3 20	277 00	52 70
6 40	3 15	1.30	430 00	44 08
5 50	3 16	2 00	330 00	48 57
5 70	3 13	2 20	280 00	51 18
6 00	3 14	0.00	440 00	38 00
6 40	3 15	0 50	340 00	37 89
5 50	3 16	1 00	290 00	30 00
5 70	3 08	2 70	450 00	56 67
6 00	3 09	3 00	424 00	60 00
6 40	3.10	3.20	300 00	64 00
5 50	3 11	1.30	460 00	44 08
5 70	3 12	2 00	410 00	50 00
6 00	3 09	2 20	310 00	48 89
6.40	3.10	0 00	470 00	40 00
5 50	3.11	0 50	420.00	34 00
5 70	3.12	1 00	320 00	34 00
6 00	2.98	2 70	426.00	55 00
6.40	2 99	3 00	328 00	49.23
5 50	3.03	3.20	277 00	50 00
5 70	3 05	1 30	430 00	31 76
6.00	3.07	2 00	330 00	46 00
6 40	2.99	2 20	280 00	40 43
5 70	3 03	0 00	440.00	28 00
6 00	3.05	0 50	340 00	20.00
6 40	3.07	1.00	290 00	24.55
5 00	3 21	2 70	450 00	49.09
5.10	3 22	3 00	424 00	53 66
5 20	3.23	3.20	300.00	42 00
5 30	3 24	1 30	460 00	35 98
5 00	3 25	2.00	410 00	40 00
5.10	3.21	2 20	310 00	44 69
5 20	3.22	0 00	470 00	33 33
5.30	3 23	0.50	420 00	32 50
5 20	3.24	1 00	320 00	31 43

Table D7 (Contd.): Results for High Modulus of Rupture

GREEN BULK DENSITY (BD)	RETAINED CARBON (RC)	METAL POWDER (MP)	OXIDATION RESISTANCE (OR)
3 22	5 00	2 70	10 38
3 23	5 10	1 30	12 18
3 24	5 20	0 00	12 78
3 13	5 30	3 00	10 04
3 13	5 10	2 00	12 20
3 14	5 20	0 50	12 33
3 15	5 70	3 20	9 50
3 16	6 00	2 20	10 82
3 13	6 40	1 00	10 20
3 08	7 80	2 70	7 20
3 09	8 30	1 30	7 50
3 10	8 40	0 00	9 00
3 11	6 60	3 00	7 80
3.12	6 70	2 00	8 54
3 08	7 30	0 50	9 80
3 09	5 70	3 20	9 55
3 10	6 00	2 20	10.82
3 11	6 40	1 00	10 20
3 12	5 10	2 70	11 00
3 09	5 20	1 30	12 04
3 10	5.30	0 00	12 17
2 98	8 70	3 00	6 73
2.99	8 80	2 00	7 00
3 03	8.90	0 50	8 08
3 05	5.10	3 20	11.00
3 07	5 20	2 20	11.96
2 98	5 30	1 00	13.00
2 99	7 80	2 70	8 76
3 03	8 30	1 30	7 87
3 05	8 40	0 00	8 33
3 07	6 60	3 00	9 13
2.98	6 70	2 00	11 54
2.99	7 30	0 50	10 23
3 03	5 70	3 20	11 00
3 05	6.00	2 20	12 82
3 07	6 40	1 00	11 27
2 95	7 80	2 70	9 47
2 96	8.30	1 30	8 89
2.97	8 40	0 00	9 86
2 97	6.60	3 00	9 33
2.98	6.70	2 00	11 50
2.95	7.30	0.50	11 00
2.96	8.70	3 20	6.69
2.97	8 80	2 20	7.29
2.97	8 90	1 00	9 24

Table D8: Results for Oxidation Resistance

RETAINED CARBON (RC)	CHEMICAL PURITY (CHP)	COKED POROSITY (CP)	SLAG CORROSION RESISTANCE (SCR)
8 70	80 00	14 50	140 00
8 80	90 00	12 20	148 00
8 90	100 00	10 00	160 00
9 00	55 00	15 00	122 85
8 70	60 00	12 50	137 89
8 80	65 00	11 00	160 00
8 90	35 00	15 50	86 68
9 00	40 00	13 20	104 68
8 80	33 00	10 50	113 78
7 70	80 00	16 00	117.14
7 80	90 00	13 00	123 33
8 30	100 00	11 50	152 50
8 40	55 00	16 50	113 32
7 70	60 00	13 10	121 00
7 80	65 00	11 90	137 20
8 30	35 00	14 50	89 26
8 40	40 00	12 20	110 09
7 80	33 00	10 00	110 54
6 60	80 00	15 00	85 00
6 70	90 00	12 50	120 00
7 30	100 00	11 00	139 00
7 00	55 00	15 50	96 43
6 60	60 00	13 20	96 47
6.70	65 00	10 50	120 00
7 30	35 00	16.00	94 12
7 00	40 00	13 00	80 78
6 70	33 00	11.50	78 72
5 50	80 00	16 50	55 00
5 70	90 00	13 10	90 20
6.00	100 00	11 90	100 00
6 40	55 00	14 50	79 26
5.50	60 00	12 20	86 36
5 70	65 00	10 00	88 75
6 00	35 00	15 00	47 26
6 40	40 00	12 50	72 87
5.70	33 00	11 00	75 97
5 00	80 00	15.50	55 00
5 10	90 00	13 20	87 50
5.20	100 00	10 50	100 00
5 30	55 00	16.00	55 00
5 00	60 00	13 00	75 00
5.10	65 00	11.50	78 57
5 20	35 00	16 50	55 00
5 30	40 00	13 10	64 23
5.10	33.00	11.90	64 45

Table D9: Results for Slag Corrosion Resistance

PLANT DATA & RULE BASE FOR MODULE-2

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD
319 5	574 5	5	129	8	134	132	55	0	1418 18	3 1
248 6	351 5	3	122	8	124 4	104 7	90	1	1418 18	3 06
359	485	6	107	14	115	112	30	0	1381 82	3 01
276	420.1	7	125	11	131	122	35	1	1483 64	3 13
272	445	7	126	13	126	120	175	0	1527 27	3 11
386	599	4	127	14	135	122	48	1	1541 82	3 11
361	570	4	130	9	130	120	108	0	1454 55	3 08
388.8	435 8	5	126 5	31 5	128	115	20	1	1403 64	3 11
370	428	7	130	33	148	122	65	1	1403 64	3 04
423	500	5 75	127	7	128	128	31	0	1534 55	3 09
440	579	5.25	104	8	135	115	26	1	1410 91	3 12
438	539	4	106	10	140	128	20	1	1541 82	3 09
416	494	4	128	11	135	125	30	1	1527 27	3 09
416	514	4	131	11	140	127	45	1	1534 55	3 09
380	440	4	123	11	135	123	45	1	1527 27	3 08
309	340	5	105	11	130	122	33	0	1556 36	3 14
286	314	6	108	8	130	117	42	1	1534 55	3 06
265	290	7	105	8	120	120	43	0	1541 82	3 11
288	301	6	105	9	120	120	38	0	1520	3 08
518	489	5	118	8	140	128	115	0	1418 18	3.02
454	389	5	132	5	150	130	135	1	1410 91	3 06
403	516	4	106	7	133	129	50	0	1410 91	3 06
395	499	4	111	7	132	127	75	0	1418 18	3 09
388	395	5	120	11	125	125	35	0	1403.64	3 08
376	420	6	124	9	130	123	25	1	1418 18	3 13
408	405	6	128	5	127	126	35	0	1418 18	3 11
392	407	5	128	5	122	122	25	0	1432 73	3 12
384	415	5	122	5	125	125	40	0	1425 45	3 11
371 2	434.3	7	119 7	8	140	124	175	0	1527 27	3 1
350	717	5	113	14	112	112	20	0	1418 18	3 09
393.3	437	4	125 3	20	144	125	170	0	1418 18	3 03
555 4	436.3	5	134	10	178	127	180	1	1410 91	3 05
255	398	10	115	8	128	128	21	0	1418 18	3 14
287	560	8 5	115	6.25	166	129	25	1	1418.18	3.13
307	630	6	119	7 5	124	124	32	0	1403 64	3 11
293	505	5	114	9	116	116	80	0	1403 64	3 05
345.7	685.9	4.5	125 9	8	130	125	10	1	1418 18	3.1
333 8	658	4	126	11	128	125	20	0	1425.45	3.15
276	453.5	4.5	123	8	118	118	40	0	1410 91	3 14
248 7	417 1	5	120.5	8	110	109	186	0	1432.73	3.1
304	517	6	120	6	145	125	25	1	1410.91	3 11
286	493	8	125 9	8	125	124	185	0	1425.45	3 09
291	513	5	124 2	5	135	125	145	0	1418.18	3 13

Table E1: Plant Data for Green Bulk Density (Contd...)

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD
284	506 6	7	91	8 5	123	114	180	0	1403 64	3 12
314	717	5	130	9	135	120	47	1	1410 91	3 13
340	441	8	118 7	18	135	130	37	0	1345.45	3 17
321 2	425 1	8	123 9	8	130	125	31	0	1585 45	3 15
330	408	6	122	12	116	114	20	0	1367 27	3 12
380	520	6	118	16	140	128	13	1	1396 36	3 11
417	602	6	118	9	143	130	25	1	1396 36	3 1
401	580	5	124	8	134	120	43	1	1418 18	3 15
389	567	5	125.2	11	135	122	17	1	1425 45	3 14
320	410	6	117	8	120	118	27	0	1396 36	3 16
292	370	7	119	11	125	121	50	0	1447 27	3 18
285	366	6	119	10	120	114	78	0	1469 09	3 15
396	536	8	124	12	157	130	25	1	1476.36	3.17
354	552	7	112.1	14	115	110	20	0	1461 82	3 15
272	482	9	115 6	10	115	114	6	0	1440	3 11
278	480	7	116.8	9	113	111	13	0	1461 82	3 09
271	472	7	114 6	12	115	112	26	0	1476 36	3 13
296	524	9	114 2	7	127	125	29	0	1410 91	3 08
285	509	9	119 5	10	125	124	45	0	1461 82	3 09
303	530	8	114.9	9	122	118	78	0	1447 27	3 13
418	556	7	113	8	135	125	30	1	1483 64	3 1
400	544	7	117	8	137	126	30	1	1345 45	3 16
396	548	6	119	8	127	127	15	0	1483 64	3 13
380	490	6	121	9	119	119	10	0	1330 91	3 17
338	418	8	106	10	148	142	15	1	1483 64	3 12
329	428	7	124	11	125	115	10	1	1483 64	3 17
344	428	7	117	11	140	118	57	1	1345 45	3 12
344	421	8	121	17	124	120	17	1	1483 64	3 05
323	401	9	126	18	150	137	5	1	1389 09	3 09
307	392	8	130	19	148	142	13	1	1447 27	3 11
308	410	8	130	19	143	135	75	0	1418 18	3 08
323	392	7	118	9	136	125	67	1	1381 82	3 14
334	467	6	119.5	8	137	127	85	1	1381 82	3.09
376	505	5	117	8	135	124	72	1	1381 82	3.03
356	487	6	123	8	138	125	79	1	1381 82	3 13
368	494	5	125	10	136	124	72	0	1381 82	3 14
377	507	6	127	7	140	128	91	0	1381 82	3 13
390	501	5	125	9	142	129	62	0	1381 82	3 12
383	583	5	128	8	138	124	25	0	1381 82	3.12
391	506	5	122	11	130	118	15	1	1418.18	3 1
394	522	4	124	5	137	121	30	1	1440	3.11
389	516	5	121	6	127	125	5	0	1476 36	3 06
375	501	4	126	4	128	126	5	0	1425 45	3.13

Table E1(Contd.). Plant Data for Green Bulk Density

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD
low	high	low	high	medium	medium	high	medium	low	medium	medium
low	low	low	medium	medium	low	very low	high	medium	medium	low
medium	medium	medium	low	high	low	very low	medium	low	low	very low
low	low	high	high	medium	medium	medium	medium	medium	high	high
low	medium	high	high	high	medium	medium	high	low	high	medium
high	high	low	high	high	medium	medium	medium	medium	high	medium
medium	high	low	high	medium	medium	medium	high	low	medium	low
high	low	low	high	high	medium	low	low	medium	low	medium
medium	low	high	high	high	high	medium	medium	medium	low	very low
high	medium	medium	high	low	medium	high	medium	low	high	medium
high	high	medium	low	medium	medium	low	low	medium	medium	medium
high	high	low	low	medium	high	high	low	medium	high	medium
high	medium	low	high	medium	medium	medium	medium	medium	high	medium
high	medium	low	high	medium	high	high	medium	medium	high	medium
high	medium	low	medium	medium	medium	medium	medium	medium	high	low
low	low	low	low	medium	medium	medium	medium	low	high	high
low	low	medium	low	medium	medium	low	medium	medium	high	low
low	low	high	low	medium	low	medium	medium	low	high	medium
low	low	medium	low	medium	low	medium	medium	low	high	low
high	medium	low	medium	medium	high	high	high	low	medium	very low
high	low	low	high	low	high	high	high	medium	medium	low
high	medium	low	low	low	medium	high	medium	low	medium	low
high	medium	low	low	low	medium	high	medium	low	medium	medium
high	low	low	medium	medium	low	medium	medium	low	low	low
medium	low	medium	medium	medium	medium	medium	low	medium	medium	high
high	low	medium	high	low	medium	medium	medium	low	medium	medium
high	low	low	high	low	low	medium	low	low	medium	medium
high	low	low	medium	low	low	medium	medium	low	medium	medium
medium	low	high	medium	medium	high	medium	high	low	high	medium
medium	high	low	low	high	low	very low	low	low	medium	medium
high	low	low	high	high	high	medium	high	low	medium	very low
high	low	low	high	medium	high	high	high	medium	medium	very low
low	low	high	low	medium	medium	high	low	low	medium	high
low	high	high	low	low	high	high	low	medium	medium	high
low	high	medium	medium	low	low	medium	medium	low	low	medium
low	medium	low	low	medium	low	low	high	low	low	very low
medium	high	low	high	medium	medium	medium	low	medium	medium	medium
medium	high	low	high	medium	medium	medium	low	low	medium	high
low	medium	low	medium	medium	low	low	medium	low	medium	high
low	low	low	medium	medium	low	very low	high	low	medium	medium
low	medium	medium	medium	low	high	medium	low	medium	medium	medium
low	medium	high	high	medium	low	medium	high	low	medium	medium
low	medium	low	high	low	medium	medium	high	low	medium	high

Table E2: Rules for Green BD from Plant Data (Contd...)

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD
low	medium	high	low	medium	low	low	high	low	low	medium
low	high	low	high	medium	medium	medium	medium	medium	medium	high
medium	medium	high	medium	high	medium	high	medium	low	low	very high
medium	low	high	medium	medium	medium	medium	medium	low	high	high
medium	low	medium	medium	medium	low	low	low	low	low	medium
high	medium	medium	medium	high	high	high	low	medium	low	medium
high	high	medium	medium	medium	high	high	low	medium	low	medium
high	high	low	medium	medium	medium	medium	medium	medium	medium	high
high	high	low	high	medium	medium	medium	low	medium	medium	high
low	low	medium	medium	medium	low	low	low	low	low	high
low	low	high	medium	medium	low	medium	medium	low	medium	very high
low	low	medium	medium	medium	low	low	high	low	high	high
high	high	high	medium	medium	high	high	low	medium	high	very high
medium	high	high	low	high	low	very low	low	low	medium	high
low	medium	high	low	medium	low	low	low	low	medium	medium
low	medium	high	medium	medium	low	very low	low	low	medium	medium
low	medium	high	low	medium	low	very low	low	low	high	high
low	medium	high	low	low	medium	medium	medium	low	medium	low
low	medium	high	medium	medium	low	medium	medium	low	medium	medium
low	high	high	low	medium	low	low	high	low	medium	high
high	high	high	low	medium	medium	medium	medium	medium	high	medium
high	high	high	medium	medium	medium	medium	medium	medium	low	high
high	high	medium	medium	medium	medium	high	low	low	high	high
high	medium	medium	medium	medium	low	low	low	low	low	very high
medium	low	high	low	medium	high	very high	low	medium	high	medium
medium	low	high	medium	medium	low	low	low	medium	high	very high
medium	low	high	medium	medium	high	low	medium	medium	low	medium
medium	low	high	medium	high	low	medium	low	medium	high	very low
medium	low	high	high	high	high	very high	low	medium	low	medium
low	low	high	high	high	high	very high	low	medium	medium	medium
low	low	high	high	high	high	very high	medium	low	medium	low
medium	low	high	medium	medium	medium	medium	medium	medium	low	high
medium	medium	medium	medium	medium	medium	high	high	medium	low	medium
medium	medium	low	medium	medium	medium	medium	medium	medium	low	very low
medium	medium	medium	medium	medium	high	medium	high	medium	low	high
medium	medium	low	high	medium	medium	medium	medium	low	low	high
medium	medium	medium	high	low	high	high	high	low	low	high
high	medium	low	high	medium	high	high	medium	low	low	medium
high	high	low	high	medium	high	medium	low	low	low	medium
high	medium	low	medium	medium	medium	low	low	medium	medium	medium
high	medium	low	medium	low	medium	medium	medium	medium	medium	medium
high	medium	low	medium	low	medium	medium	low	low	high	low
medium	medium	low	high	low	medium	medium	low	low	medium	high

Table E2 (Contd.): Rules for Green BD from Plant Data

```
MTM = H & PMT = L ==> CLASS = M
          PMT = H & GHDT = M & MT = M & FP = L & CCT = M ==> CLASS = VH
                                                 CCT = H ==> CLASS = M
          PMT = VL & CCT = M & GHDT = M ==> CLASS = VL
                               GHDT = H & MT = L & MIX = L & ST = L & ROLLS = L & FP = M & RT = L ==> CLASS = M
                                                                                           RT = H ==> CLASS = H
          PMT = M & GHDT = M ==> CLASS = M
                    GHDT = H ==> CLASS = M
                    GHDT = L ==> CLASS = VL

          PMT = VH & ST = L ==> CLASS = M
                     ST = M ==> CLASS = L

MTM = M & MIX = L & ROLLS = L & CCT = M ==> CLASS = M

                                CCT = L & RT = L & GHDT = M & MT = L ==> CLASS = VL
                                                              MT = M ==> CLASS = H
                                                   GHDT = L ==> CLASS = M

                                         RT = M & MT = L ==> CLASS = L
                                                  MT = M ==> CLASS = H

                                         RT = H & GHDT = L & PMT = M & ST = M & MT = L ==> CLASS = M
                                                                                MT = M ==> CLASS = VH
                                                  GHDT = M & FP = L ==> CLASS = M
                                                             FP = H ==> CLASS = H
                                                             FP = M ==> CLASS = M
                                                  GHDT = H ==> CLASS = H

                                CCT = H & MT = M & FP = L & GHDT = L ==> CLASS = L
                                                            GHDT = M ==> CLASS = VH

                    ROLLS = M & GHDT = L & MT = M & CCT = L ==> CLASS = L
                                                    CCT = M ==> CLASS = VH
          MIX = H & FP = M ==> CLASS = VL
                    FP = H & ROLLS = L ==> CLASS = M
                             ROLLS = M & CCT = H & RT = L ==> CLASS = M
                                                   RT = H ==> CLASS = VH
                                         CCT = M ==> CLASS = M

                    FP = L & CCT = M & MT = M & ROLLS = M & GHDT = L ==> CLASS = M
                                                            GHDT = M ==> CLASS = H
                             CCT = H ==> CLASS = M

          MIX = M & GHDT = H & ROLLS = M & PMT = L ==> CLASS = M
                                           PMT = M & RT = L & MT = M ==> CLASS = H
                                                              MT = H & ST = M ==> CLASS = H
                                                                       ST = L & FP = M & CCT = M ==> CLASS = M
                                                                                         CCT = H ==> CLASS = H
                                                     RT = H & CCT = H & ST = M & MT = L ==> CLASS = M
                                                                                 MT = M ==> CLASS = H
                               ROLLS = L & ST = M ==> CLASS = M
                                           ST = H ==> CLASS = L
                                           ST = L ==> CLASS = H

                    GHDT = L & ST = L ==> CLASS = H
                               ST = M & PMT = L ==> CLASS = L
                                        PMT = M ==> CLASS = H

                    GHDT = M & ROLLS = L ==> CLASS = H
                               ROLLS = M & CCT = M & RT = M ==> CLASS = M
                                                     RT = L ==> CLASS = VL
                                           CCT = H & MT = H ==> CLASS = M
                                                     MT = M & RT = L & PMT = M ==> CLASS = L
                                                                       PMT = L ==> CLASS = M
```

Figure E1: Decision Tree for Plant Data using ID3 (Contd...)

```
MTM = L  &  ROLLS = M  &  PMT = H  &  MIX = H  &  FP = M  &  CCT = H  ==> CLASS = L
                                                          CCT = L  ==> CLASS = H
                               PMT = M  ==> CLASS = M


          ROLLS = L  &  PMT = H  &  CCT = H  &  RT = M  ==> CLASS = M
                                                            RT = L  &  GHDT = M  &  MT = L  &  MIX = M  &  ST = M  &  FP = M  ==> CLASS = M
                                                                                                                          FP = M  ==> CLASS = L

                                        CCT = M  ==> CLASS = H

                               PMT = M  &  MIX = L  ==> CLASS = M
                                           MIX = M  &  GHDT = L  ==> CLASS = M
                                                       GHDT = M  &  RT = H  ==> CLASS = L
                                                                    RT = L  &  MT = M  ==> CLASS = L
                                                                                MT = H  ==> CLASS = H
```

Figure E1(Contd.): Decision Tree for Plant Data using ID3

APPENDIX F

MEMBERSHIP FUNCTIONS FOR MODULE-2

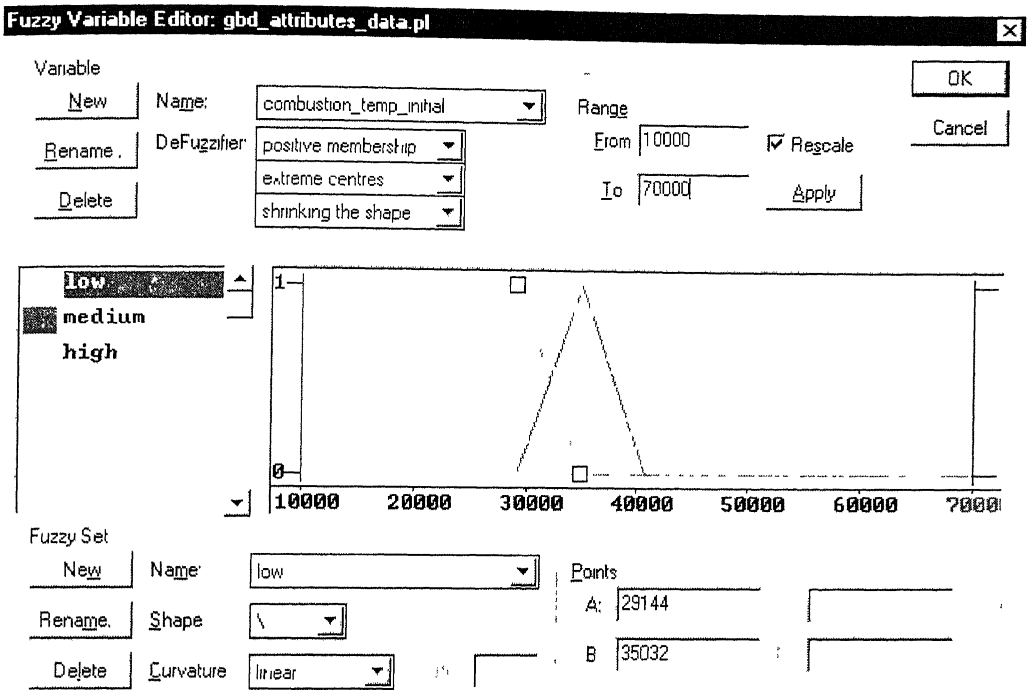


Figure F1: Membership function for Combustion Chamber Temperature

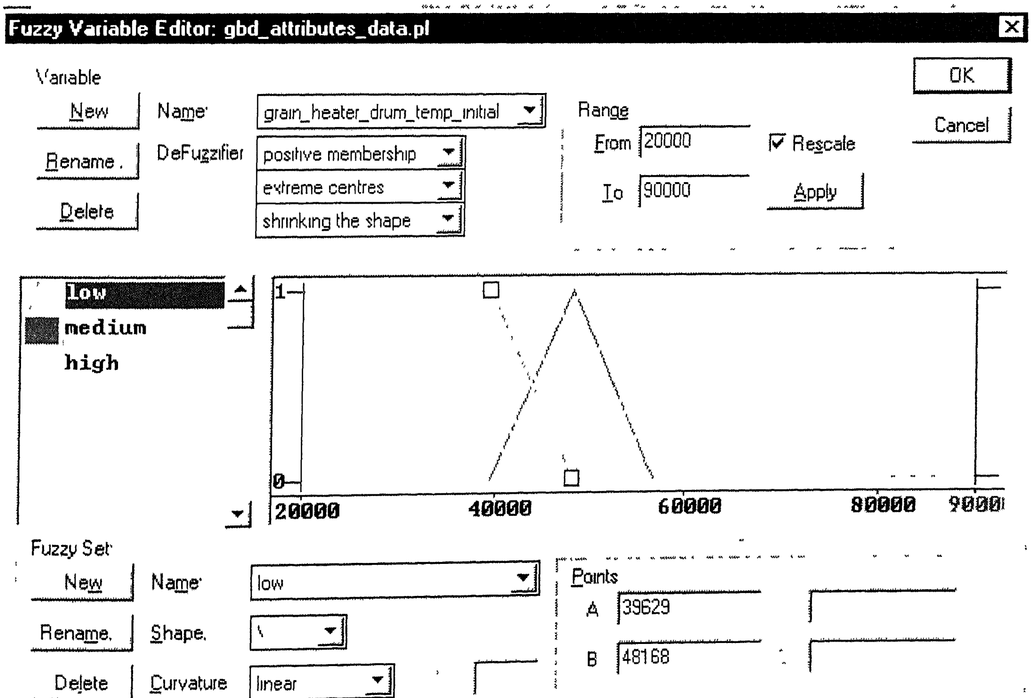


Figure F2: Membership function for Grain Heater Drum Temperature

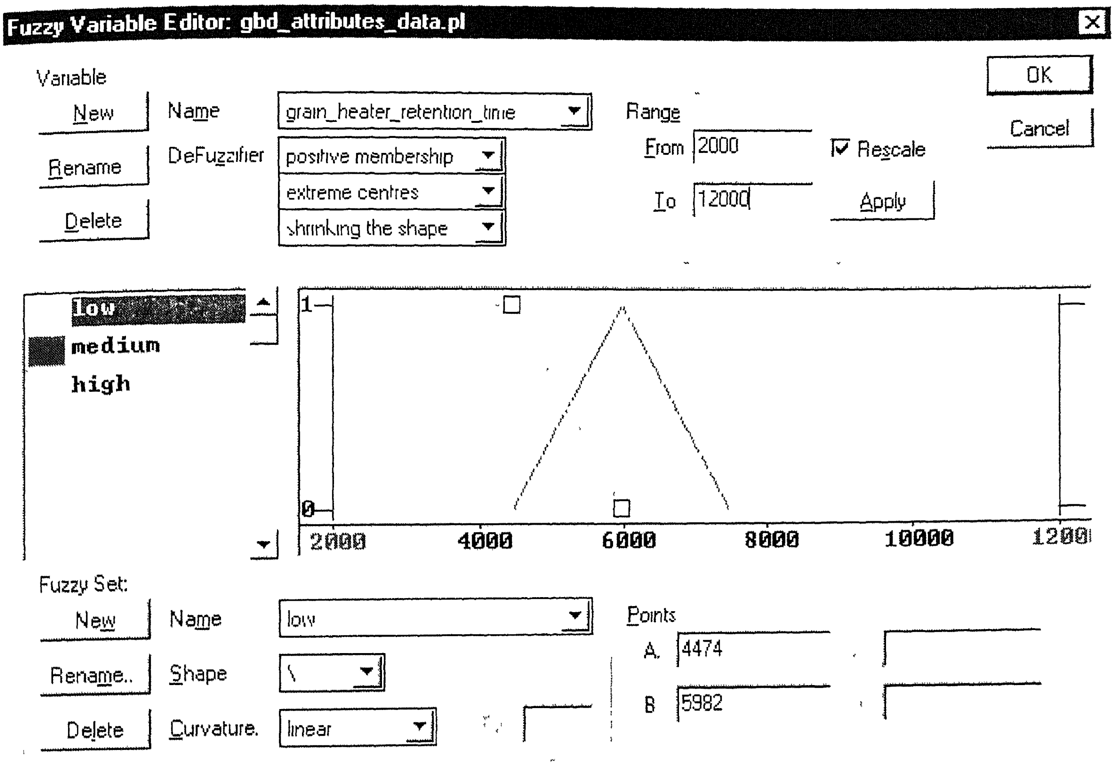


Figure F3: Membership function for Retention Time

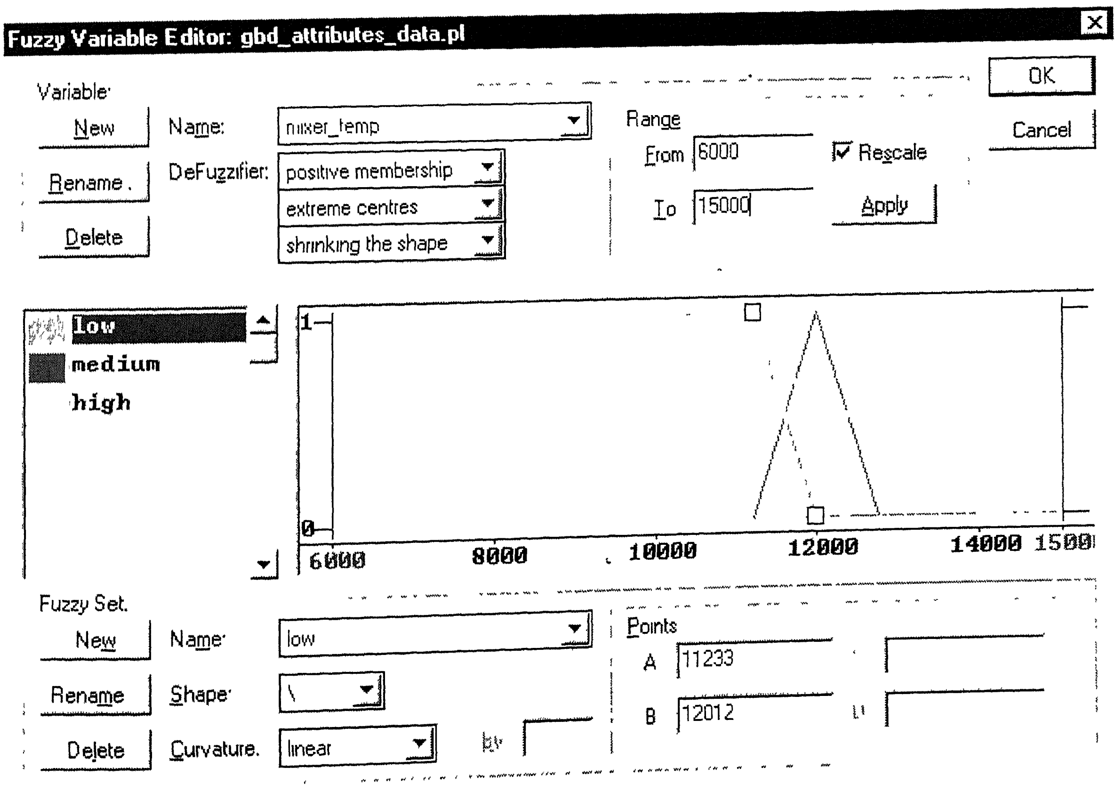


Figure F4· Membership function for Mixer Temperature

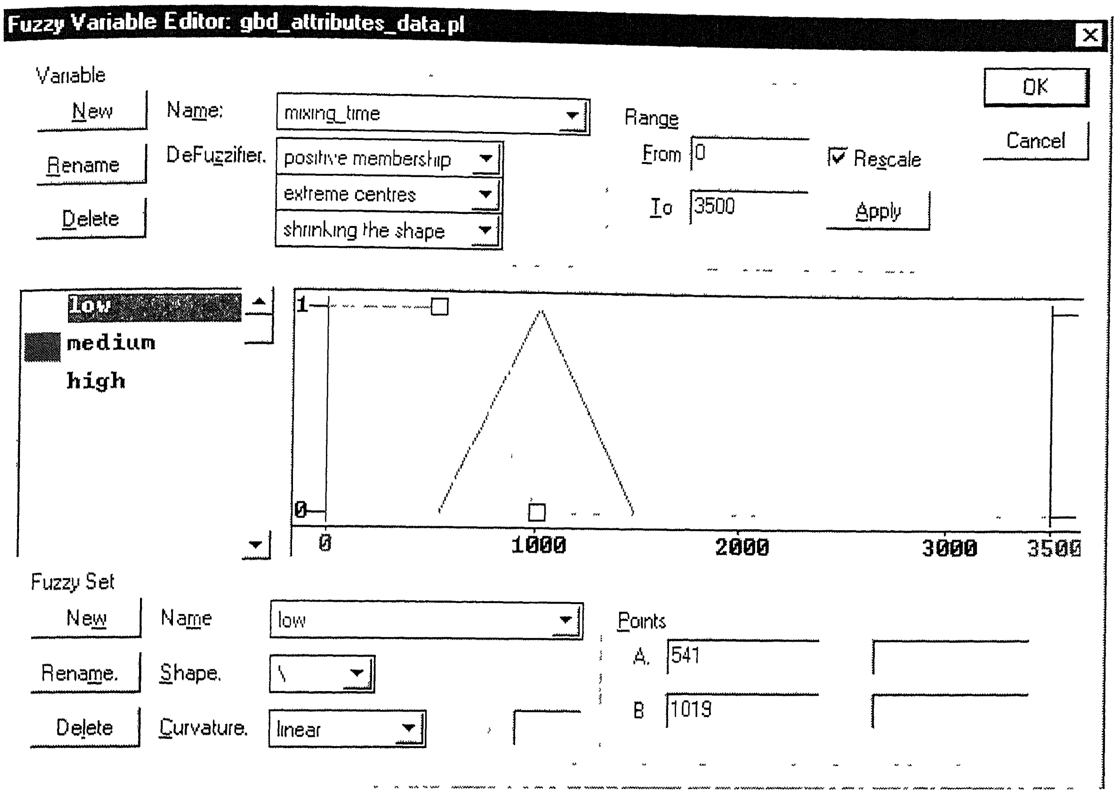


Figure F5: Membership function for Mixing Time

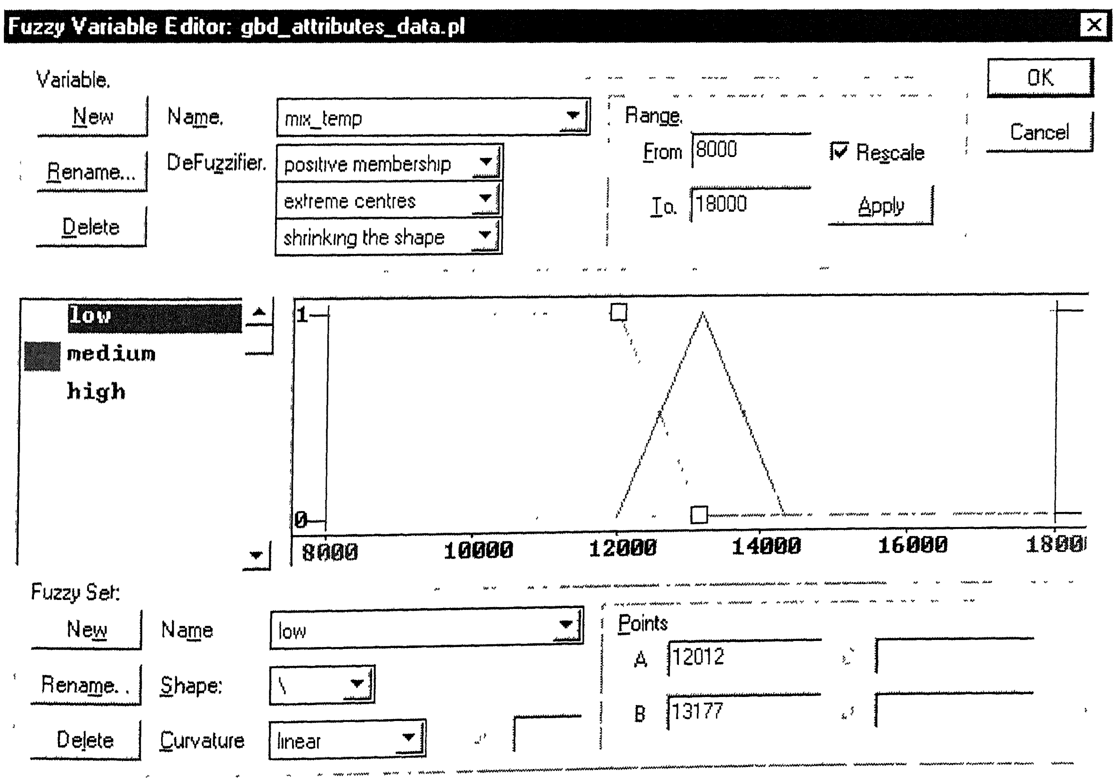


Figure F6: Membership function for Mix Temperature

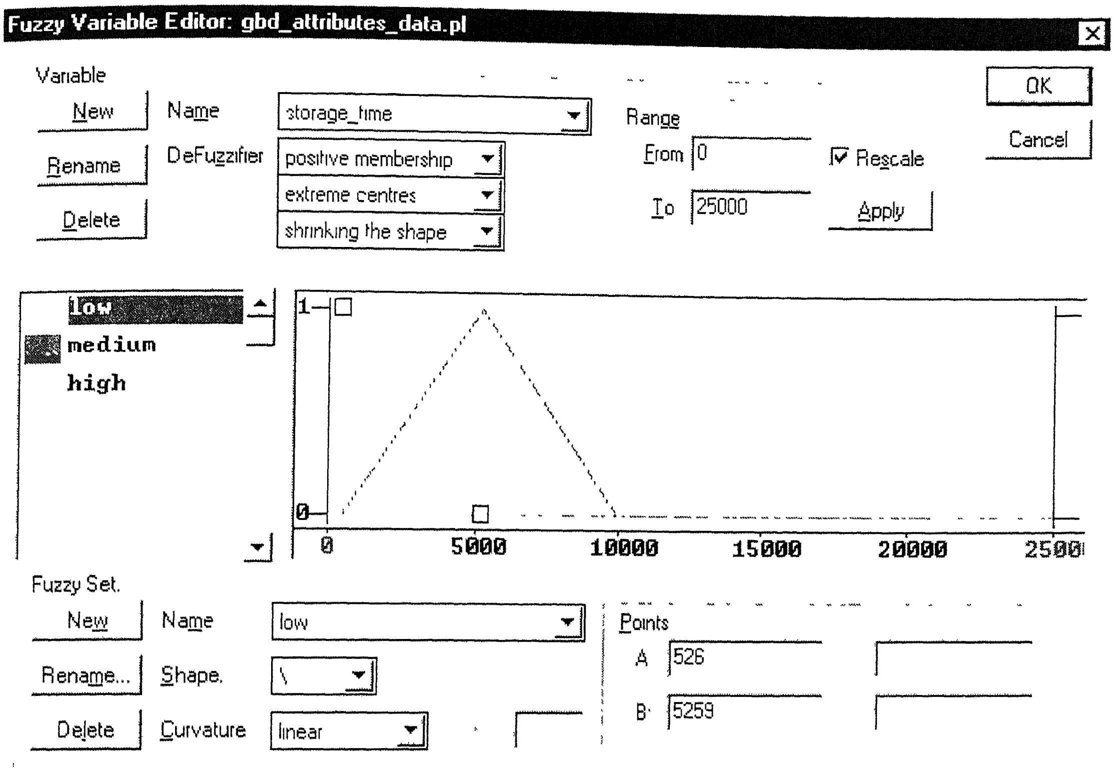


Figure F7: Membership function for Storage Time

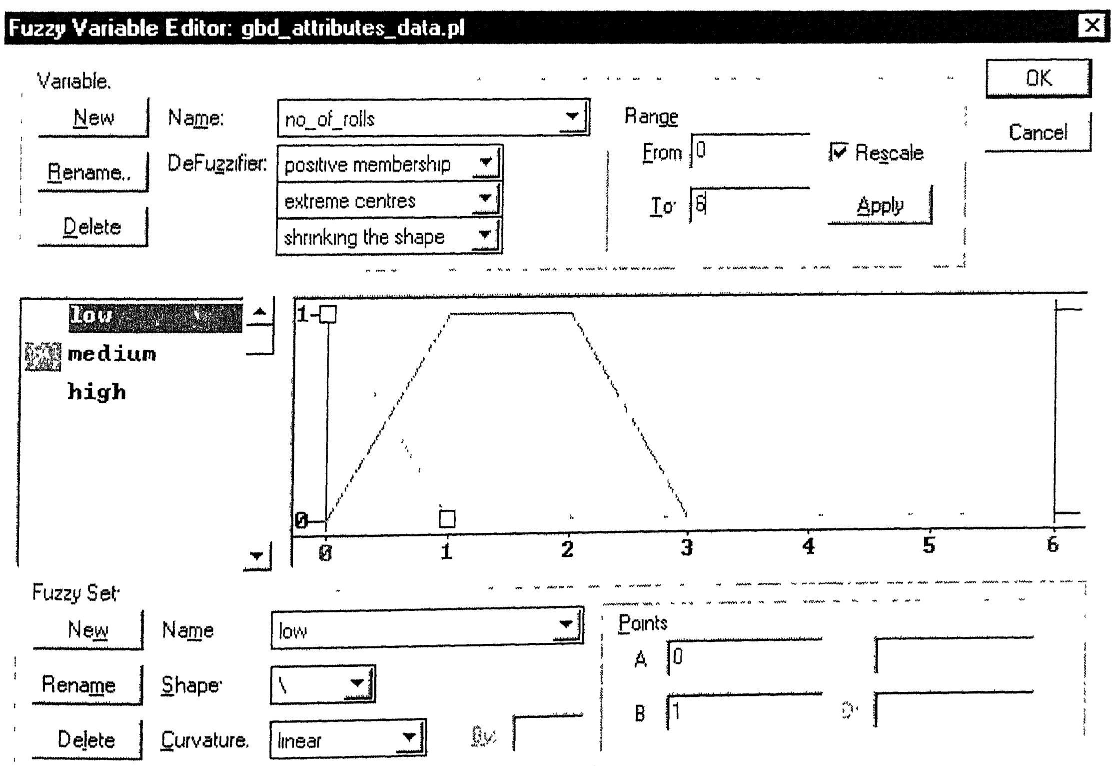


Figure F8: Membership function for Number of Rolls

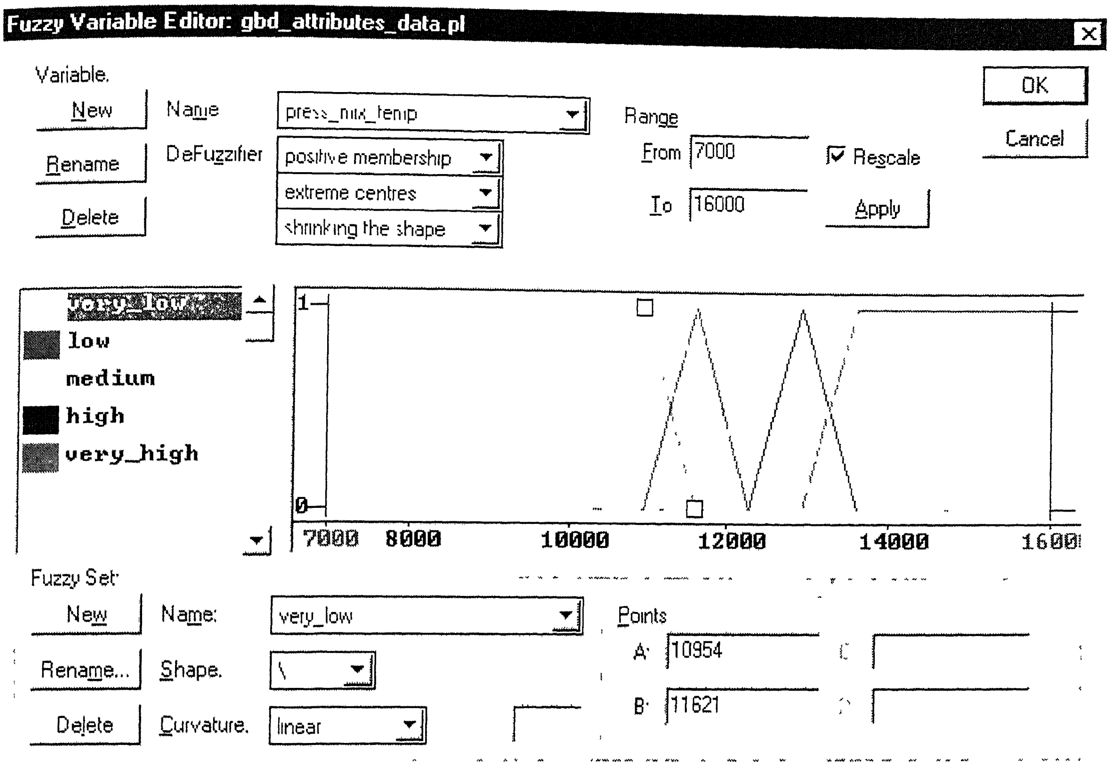


Figure F9: Membership function for Press Mix Temperature

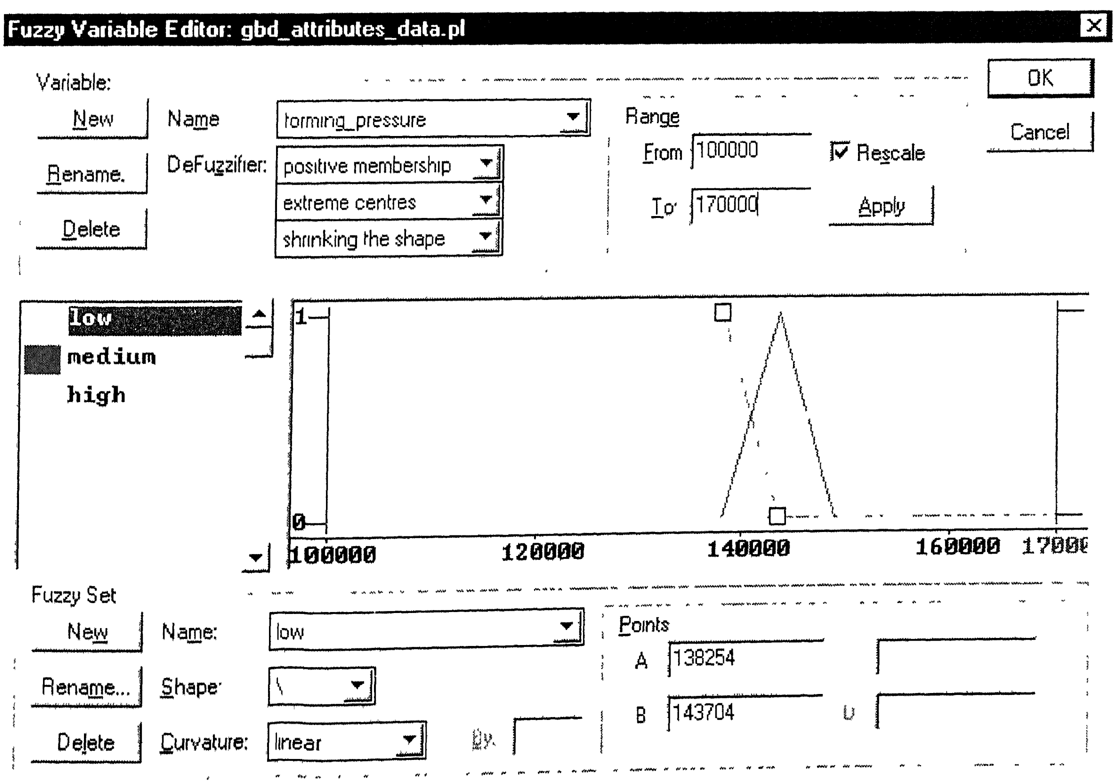


Figure F10: Membership function for Forming Pressure

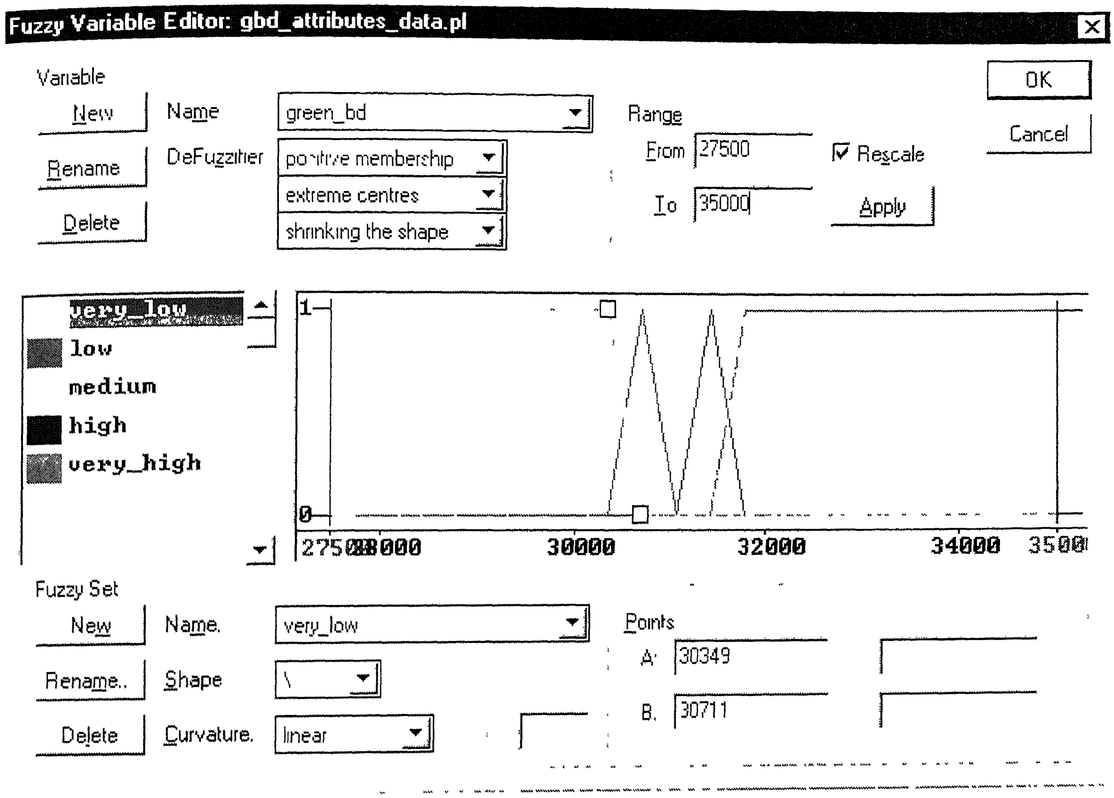


Figure F11: Membership function for Green Bulk Density

RESULTS & COMPARISONS USING PLANT DATA

GBD FROM PLANT PROCESS	GBD USING CENTROID DE-FUZZ	DEVIATION IN GBD	% DEVIATION	GBD USING PEAK DE-FUZZ	DEVIATION IN GBD	% DEVIATION
3 10	3 11	-0 01	0 24	3 11	-0 01	0 24
3 06	3 07	-0 01	0 36	3 07	-0 01	0 36
3 01	3 03	-0.02	0 83	3 05	-0 04	1 40
3 13	3 14	-0 01	0 43	3 14	-0 01	0 43
3 11	3 12	-0 01	0 29	3 11	0 00	0 09
3 11	3.11	0 00	0 09	3 11	0 00	0 09
3 08	3 07	0 01	0 29	3 07	0 01	0 29
3 11	3 11	0 00	0 09	3 11	0 00	0 09
3.04	3 03	0 01	0 17	3 05	-0 01	0 29
3 09	3.11	-0 02	0 56	3 11	-0 02	0 56
3 12	3.11	0 01	0 41	3 11	0 01	0 41
3 09	3 11	-0 02	0 56	3 11	-0 02	0 56
3 09	3 11	-0 02	0 56	3 11	-0 02	0 56
3 09	3 11	-0 02	0 56	3 11	-0 02	0 56
3 08	3 09	-0 01	0 21	3 07	0 01	0 29
3 14	3 13	0 01	0 36	3 14	0 00	0 11
3.06	3 07	-0 01	0 36	3 07	-0 01	0 36
3.11	3 09	0 02	0 52	3 11	0 00	0 09
3.08	3 07	0 01	0 26	3 07	0 01	0 29
3.02	3.03	-0 01	0 49	3 05	-0 03	1 04
3.06	3.07	-0 01	0 36	3 07	-0 01	0 36
3.06	3 09	-0.03	0 95	3 09	-0.03	0 95
3 09	3 09	0 00	0 03	3 09	0 00	0 03
3.08	3.07	0 01	0 29	3 07	0 01	0 29
3 13	3 14	-0.01	0 43	3.14	-0 01	0.43
3 11	3 11	0 00	0 09	3 11	0 00	0 09
3 12	3 11	0.01	0 20	3 11	0 01	0 41
3 11	3 12	-0 01	0 24	3 11	0 00	0 09
3 10	3 11	-0.01	0 24	3 11	-0 01	0 24
3.09	3 11	-0 02	0 56	3 11	-0 02	0 56
3.03	3.03	0.00	0.16	3 05	-0 02	0 73
3 05	3.04	0 01	0 41	3 05	0.00	0 07
3.14	3 15	-0.01	0.36	3.14	0 00	0 11
3 13	3.14	-0 01	0.43	3 14	-0 01	0 43
3.11	3 11	0 00	0.09	3 11	0.00	0 09
3.05	3.06	-0.01	0 47	3 05	0 00	0 00
3 10	3.11	-0 01	0.38	3 11	-0 01	0 24
3.15	3 13	0 02	0 54	3 14	0 01	0 21
3.14	3 14	0.00	0 11	3 14	0.00	0 11
3.10	3.11	-0 01	0 24	3 11	-0 01	0 24
3.11	3.11	0 00	0.06	3 11	0.00	0 09
3.09	3.11	-0 02	0 56	3 11	-0 02	0 56
3 13	3.14	-0.01	0 43	3 14	-0 01	0 43

Table G1: Result of Module-2 (Contd...)

GBD FROM PLANT PROCESS	GBD USING CENTROID DE-FUZZ	DEVIATION IN GBD	% DEVIATION	GBD USING PEAK DE-FUZZ	DEVIATION IN GBD	% DEVIATION
3 12	3 12	0 00	0 03	3 11	0 01	0 41
3 13	3 14	-0 01	0 22	3 14	-0 01	0 43
3 17	3 18	-0 01	0 31	3 16	0.01	0 24
3 15	3 14	0 01	0 21	3 14	0 01	0 21
3 12	3 12	0.00	0 01	3 11	0 01	0 41
3.11	3 11	0 00	0 09	3.11	0 00	0 09
3.10	3.11	-0 01	0 24	3 11	-0 01	0 24
3.15	3 14	0 01	0 46	3 14	0 01	0 21
3 14	3.13	0 01	0 29	3 14	0 00	0 11
3 16	3.13	0 03	1 06	3 14	0 02	0 52
3 18	3 15	0 03	0 95	3 16	0 02	0 49
3.15	3 14	0 01	0 21	3 14	0 01	0 21
3 17	3 18	-0 01	0 31	3 16	0 01	0 26
3 15	3 14	0.01	0 21	3 14	0 01	0 21
3 11	3.11	0 00	0 01	3 11	0 00	0.09
3.09	3.12	-0 03	1 08	3 11	-0 02	0 56
3 13	3 13	0 00	0 04	3 14	-0 01	0 43
3 08	3 08	0 00	0.09	3 07	0 01	0 29
3.09	3 10	-0.01	0.48	3 11	-0 02	0 56
3 13	3 12	0.01	0 28	3 14	-0 01	0 43
3 10	3.12	-0 02	0.57	3 11	-0 01	0 24
3 16	3.13	0.03	0 96	3 14	0.02	0 52
3 13	3 14	-0.01	0 43	3 14	-0 01	0 43
3.17	3.18	-0.01	0 31	3 16	0 01	0.26
3 12	3.11	0 01	0 41	3 11	0 01	0 41
3.17	3.18	-0 01	0.31	3 16	0 01	0 26
3 12	3 12	0 00	0 05	3 11	0 01	0 41
3 05	3.03	0.02	0 50	3 05	0 00	0 02
3.09	3.11	-0.02	0 56	3 11	-0 02	0 56
3.11	3.11	0.00	0 09	3 11	0 00	0 09
3.08	3.07	0.01	0 29	3 07	0 01	0 29
3.14	3.14	0 00	0 11	3 14	0 00	0 11
3.09	3.12	-0 03	1 04	3 11	-0 02	0 56
3.03	3 08	-0 05	1 58	3 05	-0 02	0 71
3.13	3 13	0.00	0 00	3 14	-0 01	0 43
3.14	3 14	0.00	0 14	3 14	0 00	0 11
3 13	3 14	-0.01	0 43	3 14	-0 01	0 43
3.12	3.12	0 00	0 13	3 11	0 01	0 41
3.12	3.11	0.01	0 41	3 11	0 01	0 41
3 10	3.10	0.00	0 05	3 11	-0.01	0 24
3 11	3.11	0.00	0 09	3 11	0 00	0 09
3 06	3.08	-0.02	0 77	3 07	-0 01	0 36
3.13	3.14	-0 01	0.43	3 14	-0 01	0 43

Table G1(Contd.): Result of Module-2

PLANT DATA	MODULE-2 WITH LINEAR MEMBERSHIP	MODULE-2 WITH MEMBERSHIP CURVATURE OF 2	MODULE-2 WITH MEMBERSHIP CURVATURE OF 0.5	MODULE-2 WITH MEMBERSHIP CURVATURE OF 6	MODULE-2 WITH MEMBERSHIP CURVATURE OF 0.1
3 1	3 1073	3 1073	3 1073	3 1073	3 1073
3 06	3 0711	3 0711	3 0711	3 0711	3 0711
3 01	3 0349	3 0349	3 0349	3 0349	3 0349
3 13	3 1435	3 1435	3 1435	3 1435	3 1435
3 11	3 119135783	3 114212657	3 122167831	3 10777075	3 124746812
3 11	3 1073	3 1073	3 1073	3 1073	3 1073
3 08	3 0711	3 0711	3 0711	3 0711	3 0711
3.11	3 1073	3 1073	3 1073	3 1073	3 1073
3 04	3 0349	3 0349	3 0349	3 0349	3 0349
3 09	3 1073	3 1073	3 1073	3 1073	3 1073
3 12	3 1073	3 1073	3 1073	3 1073	3 1073
3 09	3.1073	3.1073	3 1073	3 1073	3 1073
3 09	3.1073	3 1073	3 1073	3 1073	3 1073
3 09	3 1073	3 1073	3 1073	3 1073	3 1073
3 08	3 086416555	3 083762795	3 087799802	3 075983706	3 088919398
3 14	3 128595668	3 138749088	3 119185636	3 143466057	3 109787813
3 06	3 0711	3 0711	3 0711	3 0711	3 0711
3 11	3.093729461	3 097640326	3 091516335	3 105461759	3 089668343
3.08	3 071844797	3.071116441	3 07566503	3 0711	3 085732362
3 02	3.0349	3 0349	3 0349	3 0349	3 0349
3 06	3.0711	3 0711	3 0711	3 0711	3 0711
3 06	3 0892	3 0892	3 0892	3 0892	3 0892
3 09	3 0892	3.0892	3 0892	3 0892	3 0892
3.08	3 0711	3 0711	3 0711	3 0711	3 0711
3.13	3.1435	3 1435	3 1435	3 1435	3 1435
3.11	3 1073	3.1073	3 1073	3 1073	3 1073
3.12	3 113709754	3 108966186	3 118720675	3 107305422	3 123990135
3 11	3.117326082	3.112063707	3 121097758	3.107458876	3 124515477
3 1	3.1073	3.1073	3 1073	3 1073	3 1073
3 09	3 1073	3.1073	3 1073	3 1073	3 1073
3.03	3.0349	3 0349	3 0349	3.0349	3 0349
3 05	3.037460566	3.035110503	3.042734935	3 034900007	3 050683468
3 14	3.151160171	3.149041776	3.144886023	3 143757279	3 130148304
3 13	3 1435	3 1435	3 1435	3 1435	3 1435
3.11	3.1073	3 1073	3 1073	3 1073	3 1073
3 05	3 064240022	3.048432276	3 075831093	3 03530876	3 08644332
3.1	3 111879067	3.108052321	3 117266223	3.107300384	3 123651046
3 15	3 1328866	3.137488054	3 129555131	3 142922714	3 126299483
3 14	3.1435	3.1435	3.1435	3 1435	3 1435
3.1	3 1073	3.1073	3 1073	3 1073	3 1073
3 11	3.108108958	3.107319083	3 112059048	3 1073	3 122022041
3.09	3 1073	3.1073	3.1073	3 1073	3 1073
3 13	3.1435	3.1435	3.1435	3.1435	3 1435

Table G2: Module-2 output with change in shape of Membership Functions (Contd...)

PLANT DATA	MODULE-2 WITH LINEAR MEMBERSHIP	MODULE-2 WITH MEMBERSHIP CURVATURE OF 2	MODULE-2 WITH MEMBERSHIP CURVATURE OF 0.5	MODULE-2 WITH MEMBERSHIP CURVATURE OF 6	MODULE-2 WITH MEMBERSHIP CURVATURE OF 0.1
3 12	3 119063499	3.114383087	3 121979283	3 108084705	3 124687399
3 13	3 136822799	3 141722447	3.131823569	3 143494857	3 126741291
3 17	3 1797	3 1797	3 1797	3 1797	3 1797
3 15	3 1435	3 1435	3 1435	3 1435	3 1435
3 12	3 120226655	3 116363017	3 122639933	3 109339129	3 124819915
3 11	3 1073	3 1073	3 1073	3 1073	3 1073
3 1	3 1073	3 1073	3 1073	3 1073	3 1073
3 15	3 135637392	3 140912241	3 131010548	3 143483483	3 126558693
3 14	3.130930022	3 134910394	3 126592447	3 141600949	3 10704466
3 16	3 126575149	3.126481058	3 129547079	3 128413067	3 139343819
3 18	3.149674773	3 169467638	3 135235026	3 179638193	3 126417203
3 15	3.1435	3.1435	3 1435	3 1435	3 1435
3 17	3.1797	3 1797	3 1797	3 1797	3 1797
3.15	3.1435	3 1435	3 1435	3 1435	3 1435
3 11	3 110398437	3 107626807	3 115741725	3 107300036	3 123245716
3 09	3 123234613	3 121145386	3 124268258	3.114936373	3 125170277
3.13	3 131312585	3 136216066	3 128574344	3 142813922	3 126047061
3 08	3 082817149	3 077846335	3 085902638	3 07152994	3 088533381
3.09	3 104826653	3 107106017	3 099616245	3 107299994	3 091563097
3 13	3.121362509	3.131787628	3 114567962	3 142820198	3 108760033
3.1	3.117529583	3.109215512	3 128185585	3 107301508	3 140239195
3 16	3.129623226	3 133382799	3 127545667	3 141432252	3 12583184
3 13	3.1435	3 1435	3 1435	3 1435	3 1435
3 17	3 1797	3.1797	3 1797	3 1797	3 1797
3 12	3 1073	3.1073	3 1073	3 1073	3 1073
3.17	3.1797	3 1797	3.1797	3 1797	3 1797
3.12	3.118494119	3.113633998	3 121732175	3 107791817	3.124640877
3.05	3 0349	3 0349	3 0349	3 0349	3 0349
3.09	3.1073	3.1073	3 1073	3 1073	3 1073
3 11	3.1073	3.1073	3 1073	3 1073	3 1073
3 08	3 0711	3 0711	3 0711	3 0711	3 0711
3.14	3.1435	3.1435	3 1435	3 1435	3 1435
3 09	3 122275472	3 119428342	3 123810797	3 111799015	3 125078746
3 03	3 077723081	3 061191896	3 086792707	3 037166723	3 093640601
3 13	3.130005068	3.133990805	3 12775146	3 14181433	3 125874658
3 14	3.135478851	3 140664869	3 130967145	3 143469397	3.126561778
3 13	3.1435	3 1435	3.1435	3.1435	3 1435
3.12	3.116021082	3.110877437	3 120224207	3 107378189	3 124310337
3 12	3.1073	3 1073	3 1073	3 1073	3.1073
3 1	3.10168605	3.105300322	3 098784395	3.107355621	3 095983703
3.11	3 1073	3 1073	3.1073	3 1073	3 1073
3.06	3 083616163	3.074273339	3 093696527	3 071109646	3 104419471
3.13	3.1435	3 1435	3 1435	3.1435	3 1435

Table G2 (Contd): Module-2 output with change in shape of Membership Functions

MIX TEMP FROM PLANT DATA	MIX TEMP FROM MODULE-1	DEVIATION IN MIX TEMP %	PRESS MIX TEMP FROM PLANT DATA	PRESS MIX TEMP FROM MODULE-1	DEVIATION IN PMT %	GBD FROM PLANT DATA	GBD FROM MODULE-1	GBD FROM MODULE-2	DEVIATION IN GBD FROM PLANT DATA %
134 00	125 85	6.08	132 00	114 49	13 27	3 10	3 09	3 11	0 45
124 40	102 61	17.52	104 70	98 88	5 56	3 06	3 04	3 07	1 18
115 00	135 03	17 41	112 00	126.12	12 61	3 01	3 09	3 03	1 66
131 00	123 02	6 10	122 00	112 50	7 79	3 13	3 10	3 14	1 40
126 00	126.75	0 60	120 00	116.72	2 73	3 11	3 10	3 12	0 62
135 00	120 00	11.11	122 00	112 50	7 79	3 11	3 10	3 11	0 24
130 00	120.00	7 69	120 00	112 50	6 25	3 08	3 10	3 07	0 93
128 00	125 37	2.05	115 00	113.35	1 43	3 11	3 09	3 11	0 55
148 00	136 35	7.87	122 00	126 12	3 38	3 04	3 09	3 03	1 80
128 00	140 00	9.38	128 00	126 12	1 47	3 09	3 10	3 11	0 24
135.00	127.46	5 58	115 00	118 59	3 12	3 12	3 09	3 11	0 59
140.00	120 00	14 29	128 00	112 50	12.11	3.09	3 10	3 11	0 24
135 00	120.00	11 11	125 00	112 50	10 00	3 09	3 10	3 11	0 24
140 00	120 00	14 29	127.00	112 50	11 42	3 09	3 10	3 11	0 24
135 00	114 00	15 56	123 00	109.09	11 31	3 08	3 09	3 09	0 13
130.00	103.98	20.01	122 00	98 88	18 95	3 14	3 10	3 13	0 92
130.00	107 23	17.51	117.00	98 88	15.49	3 06	3 09	3 07	0 49
120.00	105.00	12 50	120.00	98.88	17 60	3 11	3 09	3 09	0 04
120 00	105 29	12.25	120 00	98 88	17 60	3 08	3.07	3 07	0 09
140 00	133.19	4.87	128 00	126 12	1 47	3 02	3 09	3 03	1 89
150 00	118.35	21.10	130.00	112.50	13 46	3 06	3 09	3 07	0 67
133 00	120.00	9.77	129.00	112 50	12 79	3 06	3.09	3 09	0 08
132.00	119.82	9.23	127.00	112.50	11 42	3 09	3 09	3 09	0.13
125.00	118.93	4.86	125.00	112 50	10 00	3 08	3 09	3 07	0 62
130.00	136.14	4 72	123.00	126.12	2.54	3 13	3 09	3 14	1 62
127 00	135.17	6.43	126.00	126.12	0.10	3 11	3 09	3 11	0 45
122 00	121.15	0.69	122.00	112.50	7 79	3 12	3 10	3 11	0 56
125.00	122.71	1.83	125.00	112.50	10 00	3 11	3 09	3 12	0 73
140 00	136.66	2.39	124.00	126 12	1 71	3.10	3.10	3 11	0.24
112 00	135 00	20.54	112.00	126.12	12.61	3 09	3 09	3 11	0 45
144.00	120.00	16.67	125.00	112 50	10 00	3 03	3 09	3 03	1 89
178 00	125.45	29.53	127.00	113.53	10.61	3 05	3 09	3 04	1 76
128.00	119.42	6.70	128.00	112 50	12.11	3 14	3 09	3 15	1 87
166.00	135.00	18.67	129.00	126.12	2 23	3 13	3 09	3 14	1 62
124.00	135.51	9.29	124 00	126 12	1 71	3 11	3 09	3 11	0 55
116.00	120.00	3.45	116.00	112 50	3 02	3 05	3 09	3 06	0 85
130 00	125.72	3.29	125 00	114.17	8 66	3.10	3 09	3 11	0.60
128.00	115.14	10 05	125.00	112.50	10 00	3 15	3 09	3.13	1 23
118 00	112 50	4.66	118.00	106.31	9.91	3 14	3 07	3 14	2 40
110 00	120 00	9 09	109 00	112 50	3 21	3 10	3 10	3 11	0.36
145 00	135 28	6 70	125 00	126 12	0 90	3 11	3 09	3 11	0 53
125 00	133.95	7.16	124.00	126.12	1 71	3 09	3 09	3.11	0 40
135.00	120.00	11.11	125.00	112 50	10 00	3 13	3 09	3 14	1 62

Table G3: Module-1 results on Plant Data (Contd…)

MIX TEMP FROM PLANT DATA	MIX TEMP FROM MODULE-1	DEVIATION IN MIX TEMP %	PRESS MIX TEMP FROM PLANT DATA	PRESS MIX TEMP FROM MODULE-1	DEVIATION IN PMT %	GBD FROM PLANT DATA	GBD FROM MODULE-1	GBD FROM MODULE-2	DEVIATION IN GBD FROM PLANT DATA %
123 00	120 00	2 44	114 00	112 50	1 32	3 12	3 09	3 12	0 93
135 00	124 20	8 00	120 00	112 50	6 25	3 13	3 09	3 14	1 46
135 00	135 89	0 66	130 00	126 12	2 98	3 17	3 08	3 18	3 26
130 00	131 10	0 85	125 00	126 12	0 90	3 15	3 10	3 14	1 40
116 00	130 04	12 10	114 00	126 12	10 63	3 12	3 08	3 12	1 20
140 00	145 00	3 57	128 00	135 00	5 47	3 11	3 09	3 11	0 60
143 00	145 00	1 40	130 00	135 00	3 85	3 10	3 09	3 11	0 60
134 00	135 00	0 75	120.00	126 12	5 10	3 15	3.09	3 14	1 37
135 00	135 00	0 00	122 00	126 12	3 38	3 14	3 09	3 13	1 17
120 00	128 18	6 82	118 00	120 58	2 19	3 16	3 08	3 13	1 37
125.00	115 50	7 60	121.00	112 50	7.02	3 18	3 10	3 15	1 62
120 00	114 90	4 25	114 00	112 13	1 64	3 15	3 10	3 14	1 40
157 00	145 00	7 64	130.00	135 00	3 85	3 17	3 10	3 18	2 57
115.00	145 00	26 09	110 00	135 00	22 73	3 15	3 10	3 14	1 40
115 00	131 35	14 22	114 00	126 12	10 63	3 11	3 10	3 11	0 40
113 00	131 59	16.45	111 00	126 12	13 62	3 09	3 10	3 12	0 75
115 00	129 88	12 94	112 00	125 72	12 25	3 13	3 10	3 13	1 01
127 00	135 00	6.30	125 00	126 12	0 90	3 08	3 09	3 08	0 29
125 00	135 00	8 00	124 00	126 12	1 71	3 09	3 10	3 10	0 16
122 00	135 38	10 97	118 00	126 12	6 88	3 13	3 10	3 12	0 71
135.00	145 00	7 41	125 00	135 00	8 00	3 10	3 10	3 12	0 57
137.00	145.00	5 84	126 00	135 00	7 14	3 16	3 08	3 13	1 63
127 00	145 00	14 17	127 00	135 00	6 30	3 13	3 10	3 14	1 40
119 00	141 67	19 05	119 00	127 60	7 23	3 17	3 08	3 18	3 35
148.00	129 00	12 84	142 00	122 98	13 40	3.12	3 10	3 11	0 24
125 00	133 20	6.56	115 00	126 12	9 67	3 17	3 10	3 18	2 57
140 00	135 64	3 12	118.00	126 12	6 88	3 12	3.08	3 12	1.27
124.00	135 43	9.22	120 00	126 12	5 10	3 05	3 10	3 03	2 10
150.00	127.13	15 25	137 00	117 70	14 09	3 09	3 09	3 11	0 69
148.00	120.97	18.26	142 00	112 50	20 77	3 11	3 10	3 11	0 25
143 00	124 91	12 65	135 00	112 50	16 67	3 08	3.09	3 07	0 72
136 00	125 28	7 88	125 00	113 28	9 38	3 14	3 09	3 14	1 86
137 00	136 07	0.68	127 00	126.12	0.69	3 09	3.09	3 12	1 17
135.00	135.00	0 00	124 00	126 12	1 71	3 03	3 09	3 08	0.27
138 00	141 90	2.83	125 00	126 12	0 90	3.13	3.09	3 13	1 42
136 00	133 71	1.68	124 00	126 12	1 71	3 14	3 09	3 14	1 60
140 00	145 00	3.57	128 00	126 12	1.47	3 13	3 09	3 14	1.86
142 00	135 00	4.93	129 00	126 12	2 23	3 12	3 09	3 12	0.97
138 00	135.00	2 17	124 00	126 12	1 71	3 12	3 09	3 11	0 69
130 00	135.00	3.85	118.00	126 12	6 88	3 10	3 09	3 10	0 27
137.00	120.00	12 41	121.00	112 50	7 02	3 11	3 10	3 11	0 30
127.00	135 00	6 30	125.00	126.12	0 90	3 06	3.10	3.08	0 53
128 00	120 00	6.25	126.00	112 50	10 71	3.13	3 09	3 14	1 57

Table G3 (Contd.): Module-1 results on Plant Data

PLANT DATA	RESULTS FROM MODULE-2	DEVIATION FROM PLANT DATA	RESULTS USING MATLAB	DEVIATION FROM PLANT DATA
3 10	3 11	-0 01	3 08	-0 02
3 06	3 07	-0 01	3 02	-0 04
3 01	3 03	-0 02	3 03	0 02
3 13	3.14	-0 01	3 13	0 00
3 11	3 12	-0.01	3 11	0 00
3 11	3 11	0 00	3 11	0 00
3 08	3 07	0 01	3 09	0 01
3 11	3 11	0 00	3 11	0 00
3 04	3 03	0 01	3 05	0 01
3 09	3 11	-0 02	3 09	0 00
3 12	3 11	0 01	3 12	0 00
3 09	3 11	-0 02	3 09	0 00
3 09	3 11	-0 02	3 10	0 01
3 09	3.11	-0 02	3 08	-0 01
3.08	3 09	-0 01	3 08	0 00
3 14	3 13	0 01	3 14	0 00
3 06	3 07	-0.01	3 06	0 00
3 11	3 09	0 02	3 11	0 00
3 08	3 07	0 01	3 08	0 00
3.02	3 03	-0 01	3 02	0 00
3 06	3 07	-0 01	3 05	-0.01
3 06	3 09	-0 03	3 10	0 04
3 09	3 09	0 00	3 09	0 00
3 08	3 07	0 01	3 10	0 02
3.13	3 14	-0.01	3 14	0 01
3 11	3 11	0 00	3 11	0 00
3 12	3 11	0.01	3 12	0 00
3 11	3 12	-0 01	3 10	-0.01
3 10	3 11	-0 01	3 10	0 00
3 09	3.11	-0 02	3 07	-0 02
3 03	3 03	0 00	3 03	0 00
3 05	3 04	0.01	3.04	-0 01
3 14	3.15	-0.01	3.12	-0.02
3.13	3.14	-0.01	3 13	0.00
3 11	3 11	0.00	3 12	0 01
3 05	3 06	-0 01	3 05	0 00
3.10	3 11	-0 01	3 10	0.00
3 15	3 13	0.02	3.12	-0 03
3 14	3 14	0 00	3 15	0 01
3.10	3 11	-0 01	3 09	-0 01
3 11	3.11	0 00	3 06	-0 05
3 09	3 11	-0.02	3 10	0 01
3 13	3.14	-0.01	3.13	0 00

Table G4: Module-2 results Compared with Result of Matlab on Plant Data (Contd...)

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD FROM MODULE-2	GBD FROM MATLAB	GBD FROM PLANT DATA
276 00	583 00	3 00	129 00	11 00	128 00	127 00	30 00	0 00	1455 00	3 11	3 10	3 10
272 00	420 10	5 75	120 00	11 00	115 00	112 00	133 00	1 00	1455 00	3 07	3 94	3 06
370 00	445 00	6 00	104 00	30 00	124.40	104 70	35 00	0 00	1404 00	3 03	3 10	3 01
319 50	351 50	7 00	127 00	11 00	128 00	120 00	30 00	1 00	1542 00	3 13	2 76	3 13
248 60	485.00	7 00	130 00	33 00	131 00	122 00	115 00	0 00	1484 00	3 11	3 10	3 11
386 00	579 00	4 75	126 50	31 50	126 00	120 00	30 00	1 00	1527 00	3 11	3 10	3 11
359 00	539 00	4 75	130 00	9 00	135 00	122 00	165 00	0 00	1411 00	3 07	3 45	3 08
388 80	428 00	5 75	127 00	13 00	130 00	117 00	10 00	1 00	1382 00	3 08	3 45	3 11
361 00	435 80	7 00	125 00	14 00	140 00	125 00	31.00	1 00	1382 00	3 07	3 77	3 04
518 00	489 00	5 25	126 00	7 00	135 00	130 00	65 00	0 00	1520 00	3 11	1 62	3 09
454 00	599 00	5 75	106 00	12 00	128 00	117 00	20 00	1 00	1425 00	3 11	3 05	3 12
403 00	570 00	4 75	104 00	12 00	148 00	130 00	26 00	1 00	1520 00	3 11	0 45	3 09
395 00	440 00	4 75	131 00	11 00	126 00	120 00	42 00	1 00	1542 00	3 11	2 74	3 09
388 00	494 00	4 75	128.00	11.00	150 00	130 00	43 00	1 00	1527 00	3 11	3 21	3 09
380 00	514 00	4 75	123 00	11 00	131 00	120 00	38 00	1 00	1535 00	3 09	3 37	3 08
255 00	290 00	5 75	108.00	11 00	126 00	125 00	30 00	0 00	1527 00	3 09	2 66	3 14
287 00	301 00	6 00	105 00	9 00	135 00	116 00	45 00	1 00	1556 00	3 07	1 93	3 06
307 00	340 00	7.00	106.00	8 00	125 00	123 00	45 00	0 00	1535 00	3 09	2 42	3 11
293 00	314 00	6 00	104 00	8.00	125 00	122 00	33 00	0 00	1542 00	3 07	2 61	3 08
423 00	500 00	5 75	120 00	8.00	150.00	129 00	135 00	0 00	1411 00	3 03	1 83	3 02
440 00	389 00	5 75	134 00	1 00	140.00	127 00	177 00	1 00	1418 00	3 07	2 52	3 06
438 00	499.00	4 75	111 00	2 00	128 00	128 00	75 00	0 00	1418 00	3 09	0 83	3 06
416 00	516 00	4 75	106 00	3 00	128 00	130 00	35 00	0 00	1411.00	3 09	3 15	3 09
416 00	405.00	5 75	124 00	12 00	116 00	122 00	50 00	0 00	1382 00	3 10	2 96	3 08
376 00	407.00	6.00	120.00	12 00	130 00	125 00	10 00	1 00	1433 00	3 14	2 79	3 13
393 30	415 00	6 00	134.00	3 00	127 00	124 00	44 00	0 00	1425 00	3 11	3 09	3 11
555 40	434 30	5 75	134.00	7 00	116 00	125 00	11 00	0 00	1418 00	3 11	3 10	3 12
384 00	395 00	5 75	119 70	4.00	116 00	123 00	40 00	0 00	1418 00	3 11	3 22	3 11
350 00	420 00	7.00	122 00	12 00	160 00	126 00	80 00	0 00	1585 00	3 11	3 42	3 10
371.20	717 00	5.75	104 00	20 00	125 00	110 00	12.00	0 00	1411 00	3 11	3 30	3 09
408 00	398 00	4 75	134 00	14 00	160 00	123 00	80 00	0 00	1433 00	3 04	2 92	3 03
392 00	437.00	5.75	125 30	8 00	150 00	129 00	90 00	1 00	1411 00	3 07	3 67	3 05
309 00	436 30	10.00	107.00	10 00	135 00	127 00	25 00	0 00	1425 00	3 14	3 17	3 14
286 00	685 90	8.50	110 00	7 50	140 00	128 00	21 00	1 00	1418 00	3 14	2 89	3 13
265 00	658.00	6.00	123 90	6 25	116 00	123 00	40 00	0 00	1345 00	3 11	3 10	3 11
288 00	505.00	5 75	104.00	12.00	124 00	117 00	180 00	0 00	1365 00	3 03	4 20	3 05
345 70	560.00	4.75	136 00	12.00	128 00	123 00	20 00	1 00	1411 00	3 11	2 16	3 10
333 80	630 00	4 75	130 00	12 00	130 00	123 00	10 00	0 00	1433 00	3 14	2 98	3 15
272 00	506 60	4.75	120 50	12 00	110 00	114 00	33 00	0.00	1411 00	3 14	2 96	3 14
278.00	417.10	5 75	120.00	12 00	118.00	112 00	86 00	0 00	1425 00	3 12	3 29	3 10
271.00	493 00	6.00	123 00	2 00	170 00	123 00	12.00	1 00	1418 00	3 11	3 10	3 11
296 00	513 00	8.00	124 20	12 00	116 00	123 00	145 00	0 00	1418 00	3 11	2 01	3 09
285 00	517 00	5 75	125 90	1.00	130 00	123 00	185 00	0 00	1425 00	3.14	-1 68	3 13

Table G5: Module-2 results Compared with Result of Matlab on Fabricated Data

(contd…)

CCT	GHDT	RT	MIXER TEMP	MIXING TIME	MIX TEMP	PMT	ST	NO OF ROLLS	FP	GBD FROM MODULE-2	GBD FROM MATLAB	GBD FROM PLANT DATA
284 00	453 50	7 00	110 00	12 00	115 00	117 00	80 00	0 00	1350 00	3 11	2 05	3 12
314 00	602 00	5 75	126 00	12 00	128 00	124 00	31 00	1 00	1433 00	3 13	2 98	3 13
330 00	441 00	8 00	122 00	21 00	128 00	128 00	47 00	0 00	1404 00	3 18	3 12	3 17
340 00	408 00	8 00	118 00	12 00	135 00	120 00	37 00	0 00	1527 00	3 14	2 42	3 15
321 20	425 10	6 00	118 00	8 00	123 00	117 00	25 00	0 00	1331 00	3 13	3 35	3 12
418 00	520 00	6 00	124 00	22 00	150 00	130 00	20 00	1 00	1331 00	3 11	5 44	3 11
400 00	717 00	6 00	118 70	12 00	170 00	128 00	13 00	1 00	1331 00	3 11	2 25	3 10
396 00	536 00	5 75	123 90	12 00	128 00	122 00	33 00	1 00	1425 00	3 10	3 16	3 15
380 00	552 00	5 75	137 00	12 00	128 00	120 00	27 00	1 00	1418 00	3 13	3 15	3 14
307 00	370 00	6 00	119 00	11 00	125 00	114 00	17 00	0 00	1367 00	3 13	3 19	3 16
308 00	366 00	7 00	124 00	8 00	120 00	124 00	33 00	0 00	1418 00	3 18	3 13	3 18
285 00	410 00	6 00	117 00	11 00	125 00	117 00	178 00	0 00	1476 00	3 14	2 86	3 15
396 00	580 00	8.00	119 00	10 00	140 00	127 00	13 00	1 00	1469 00	3 17	1 87	3 17
354 00	567 00	7.00	115 60	14 00	125 00	107 00	26 00	0 00	1440 00	3 14	3 21	3 15
276 00	524 00	9 00	112 10	10 00	122 00	117 00	25 00	0 00	1462 00	3 10	3 11	3 11
248 70	509 00	7 00	123 00	9 00	125 00	107 00	20 00	0 00	1440 00	3 11	2 21	3 09
304 00	482 00	7 00	94 00	12 00	122 00	107 00	6 00	0 00	1527 00	3 14	3 10	3 13
286 00	480 00	9 00	92.00	3 00	127 00	121 00	45 00	0 00	1447 00	3 07	3 10	3 08
291 00	472.00	9 00	122 00	8 00	113 00	121 00	29 00	0 00	1411 00	3 12	3 06	3 09
303 00	544 00	8 00	105 00	9 00	113 00	114 00	90 00	0 00	1462 00	3 14	3 51	3.13
380 00	548 00	7 00	108 00	10 00	127 00	121 00	45 00	1 00	1527 00	3 11	2 14	3 10
417 00	530 00	7 00	121 00	11 00	135 00	121 00	45 00	1 00	1400 00	3 14	2 90	3 16
401.00	556 00	6 00	117 00	10.00	137.00	130 00	10 00	0 00	1520 00	3 14	3 36	3 13
389.00	490 00	6.00	119 00	9.00	113 00	114 00	15 00	0 00	1401 00	3 18	3 17	3 17
344 00	392 00	8 00	100.00	8 00	140 00	144 00	10 00	1 00	1527 00	3 11	3 76	3 12
344 00	410.00	7 00	117 00	8 00	113 00	118 00	15 00	1 00	1527 00	3 18	3 30	3 17
323 00	392 00	7 00	121 00	8 00	166 00	118 00	34 00	1 00	1386 00	3 11	3 12	3 12
338 00	418 00	8 00	124 00	19 00	113 00	125 00	13 00	1 00	1527 00	3 03	3 19	3 05
329 00	428 00	9 00	130 00	19 00	140 00	135 00	17 00	1 00	1345 00	3 11	3 88	3 09
320 00	428 00	8 00	135 00	17.00	155 00	137 00	5 00	1 00	1418 00	3 11	2 95	3 11
292 00	421.00	8 00	126.00	18 00	165.00	142 00	35 00	0 00	1447 00	3.07	1 54	3 08
356 00	401 00	7.00	123 00	12 00	127 00	120 00	34 00	1 00	1345 00	3 14	2 59	3 14
368.00	494 00	6 00	118.00	12 00	127 00	130 00	185 00	1 00	1345 00	3 11	0 70	3 09
377 00	507 00	5 75	119 50	11 00	127 00	121 00	30 00	1 00	1345 00	3 03	3 14	3 03
323 00	501 00	6 00	117 00	11.00	145 00	121 00	111 00	1 00	1345 00	3 14	-0 12	3 13
334 00	467 00	5.75	128 00	8 00	127 00	121 00	112 00	0 00	1401 00	3 14	1 25	3 14
376 00	505 00	6 00	125.00	3 00	150 00	129 00	112 00	0 00	1401.00	3 14	1 89	3 13
391 00	487.00	5 75	127.00	11.00	154 00	128 00	32 00	0 00	1401 00	3 11	3 14	3 12
394 00	574 50	5 75	125.00	12.00	140.00	121 00	15 00	0 00	1401 00	3 13	3 16	3 12
389 00	516 00	5 75	121.00	8 00	127 00	114 00	25 00	1 00	1440 00	3 11	3 38	3 10
390.00	501 00	4.75	122.00	2 00	128 00	126 00	44 00	1 00	1418 00	3 11	3 16	3 11
383 00	506 00	5.75	124.00	2 00	130.00	121 00	21 00	0 00	1520 00	3 07	2 92	3 06
375 00	522 00	4 75	132.00	7 00	137 00	125.00	21 00	0 00	1418 00	3 13	3 07	3 13

Table G5 (Contd.): Module-2 results Compared with Result of Matlab on Fabricated Data

APPENDIX H

ASSESSING PROBABILITIES FROM BAYESIAN NETWORK

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0207	0.1047	0.2995	0.2770	0.2981
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1111	0.2778	0.4444	0.1667	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1111	0.2469	0.3951	0.2469	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.1591	0.3059	0.5350		

Table H1: Prior Probabilities

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0252	0.1137	0.3026	0.2793	0.2792
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1667	0.3333	0.5000	0.0000	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1667	0.2963	0.4259	0.1111	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.2058	0.3621	0.4321		

Table H2: Probabilities with CTI = HIGH

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0236	0.1112	0.3026	0.2785	0.2841
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1667	0.3333	0.3333	0.1667	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.1667	0.2963	0.3148	0.2222	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.2058	0.3251	0.4691		

Table H3: Probabilities with CTI=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0132	0.0893	0.2933	0.2733	0.3310
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0000	0.1667	0.5000	0.3333	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0000	0.1481	0.4444	0.4074	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.0658	0.2305	0.7037		

Table H4: Probabilities with CTI=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0291	0.1227	0.3075	0.2812	0.2594
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.3333	0.3333	0.3333	0.0000	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.3333	0.2963	0.2963	0.0741	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.2798	0.3745	0.3457		

Table H5. Probabilities with CTI=HIGH, GHDT=HIGH

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0214	0.1046	0.2977	0.2774	0.2989
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0000	0.3333	0.6667	0.0000	0.0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0000	0.2963	0.5556	0.1481	0.0000
PMT	HIGH	MEDIUM	LOW		
	0.1317	0.3498	0.5185		

Table H6: Probabilities with CTI=HIGH, GHDT=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0412	0 1460	0 3152	0 2872	0 2104
GT	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	1 0000	0 0000	0 0000	0 0000
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 8889	0 1111	0 0000	0 0000
PMT	HIGH	MEDIUM	LOW		
	0 3951	0 5309	0 0741		

Table H7: Probabilities with CTI=MEDIUM, GHDT=MEDIUM, RT=HIGH

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1531	0 3185	0 2889	0 1951
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	1 0000	0 0000	0 0000	0 0000
PMT	HIGH	MEDIUM	LOW		
	0 4444	0 5556	0 0000		

Table H8 Probabilities with GT=HIGH, MT=HIGH OR MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0.0346	0 1317	0 3086	0 2840	0 2412
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 6667	0 3333	0 0000	0 0000
PMT	HIGH	MEDIUM	LOW		
	0 2963	0 4815	0 2222		

Table H9: Probabilities with GT=HIGH, MT=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1531	0 3185	0 2889	0 1951
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	1 0000	0 0000	0 0000	0 0000
PMT	HIGH	MEDIUM	LOW		
	0 4444	0 5556	0 0000		

Table H10: Probabilities with GT=HIGH, MT=LOW, MTM=HIGH / MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0148	0 0889	0 2889	0 2741	0 3333
MIX TEMP	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	1 0000	0 0000	0 0000
PMT	HIGH	MEDIUM	LOW		
	0 0000	0 3333	0 6667		

Table H11: Probabilities with GT=HIGH, MT=LOW, MTM=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1481	0 3111	0 2889	0 2074
PMT	HIGH	MEDIUM	LOW		
	0 3333	0 6667	0 0000		

Table H12: Probabilities with MIX=HIGH, ST=HIGH OR MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1630	0 3333	0 2889	0 1704
PMT	HIGH	MEDIUM	LOW		
	0 6667	0 3333	0 0000		

Table H13: Probabilities with MIX=HIGH, ST=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0148	0 0889	0 2889	0 2741	0 3333
PMT	HIGH	MEDIUM	LOW		
	0 0000	0.3333	0 6667		

Table H14 Probabilities with MIX=MEDIUM, ST=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0667	0 2889	0 2667	0 3778
PMT	HIGH	MEDIUM	LOW		
	0 0000	0 0000	1 0000		

Table H15: Probabilities with MIX=LOW, ST=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1333	0 2889	0 2889	0 2444
PMT	HIGH	MEDIUM	LOW		
	0 0000	1 0000	0 0000		

Table H16· Probabilities with MIX=MEDIUM,ST=LOW,ROLLS=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0444	0 1778	0 3556	0 2889	0 1333
PMT	HIGH	MEDIUM	LOW		
	1 0000	0 0000	0 0000		

Table H17: Probabilities with MIX=HIGH,ST=LOW,ROLLS=LOW

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	0 0000	0 3333	0 6667

Table H18· Probabilities with PMT=HIGH, GQ=VERY HIGH

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	0 7778	0 2222	0 0000

Table H19· Probabilities with PMT=HIGH, GQ=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	1 0000	0 0000	0 0000

Table H20: Probabilities with PMT=HIGH, GQ=MEDIUM, PQ=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	0 0000	1 0000	0 0000

Table H21: Probabilities with PMT=LOW, GQ=MEDIUM, PQ=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	0 6667	0 3333	0 0000

Table H22· Probabilities with PMT=MEDIUM, GQ=MEDIUM, PQ=MEDIUM

Node Name	State 0	State 1	State 2	State 3	State 4
GBD	VERY HIGH	HIGH	MEDIUM	LOW	VERY LOW
	0 0000	0 0000	1 0000	0 0000	0 0000

Table H23: Probabilities with PMT=MEDIUM, GQ=MEDIUM, PQ=MEDIUM, FP= HIGH OR MEDIUM

APPENDIX I

MARS RESULT

```
BOPTIONS SPEED = 4, PENALTY = 0.000000, BASIS = 12, INTERACTIONS = 2
BOPTIONS MINSPAN = 0
LIMIT DATASET = 0
RECORDS READ· 128
RECORDS KEPT IN LEARNING SAMPLE: 128
```

LEARNING SAMPLE STATISTICS

VARIABLE	MEAN	SD	N	SUM
GBD	3.103	0.035	128.000	397.120
CTI	357.759	51.032	128.000	45793 200
GHDT	484.013	74.824	128.000	61953 700
RT	6.090	1.515	128.000	779.500
MIXER_TE	119.841	8.245	128.000	15339.600
MIXING_T	11.561	5.443	128.000	1479.750
MIX_TEMP	133.941	10.859	128.000	17144.400
PMT	125.271	7.288	128.000	16034.700
ST	51 125	45.431	128.000	6544 000
NO_OF_RO	0 508	0.517	128 000	65.000
FP	1426.180	58.891	128.000	182551.000

Ordinal Response

	min	Q25	Q50	Q75	max
GBD	3.010	3 080	3 110	3.130	3 180

Ordinal Predictor Variables: 10

	min	Q25	Q50	Q75	max
CTI	248 600	323 000	364.000	389 000	555.400
GHDT	290 000	428 000	493 000	519.000	717.000
RT	3.000	5 000	6.000	7.000	13.000
MIXER_TE	91.000	115 000	121.000	126 000	135.000
MIXING_T	4.000	8.000	10.000	14.000	33.000
MIX_TEMP	110.000	127.000	135.000	140.000	178.000
PMT	104.700	121.000	125.000	129.000	144.000
ST	5.000	20.000	33.000	72.000	210.000
NO_OF_RO	0.000	0.000	0.000	1.000	2.000
FP	1258.000	1382 000	1418.000	1476.000	1585 000

Forward Stepwise Knot Placement

BasFn(s)	GCV	IndBsFns	EfPrms	Variable	Knot	Parent	BsF
0	0.001	0.0	1.0				
2 1	0.001	2.0	6 0	MIXER_TE	127.000		
4 3	0.001	4 0	11 0	MIXING_T	10.000		
6 5	0.001	6.0	16 0	RT	7 000		
7	0.001	7 0	20 0	ST	5.000	RT	6
9 8	0.001	9 0	25 0	MIXER_TE	114.000	RT	6
11 10	0 001	11.0	30.0	NO_OF_RO	1.000	RT	6
12	0.001	12.0	34 0	CTI	248.600	RT	6

Final Model (After Backward Stepwise Elimination)

Basis Fun	Coefficient	Variable	Parent	Knot
0	3.120			
3	-0.003	MIXING_T		10.000
7	-.160212E-03	ST	RT	5.000
8	.996742E-03	MIXER_TE	RT	114.000
12	-.758248E-04	CTI	RT	248.600

Piecewise Linear GCV = 0 001, #efprms = 12 000

ANOVA Decomposition on 4 Basis Functions

fun	std. dev.	-gcv	#bsfns	#efprms	variable	
1	0.012	0 001	1	2 750	MIXING_T	
2	0 014	0.001	1	2 750	RT	ST
3	0.013	0 001	1	2.750	RT	MIXER_TE
4	0 012	0 001	1	2.750	CTI	RT

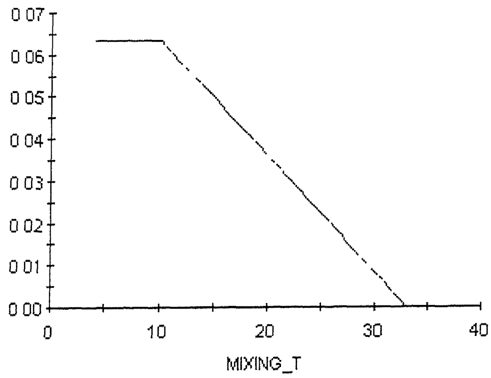
Piecewise Cubic Fit on 4 Basis Functions, GCV = 0 001

Relative Variable Importance

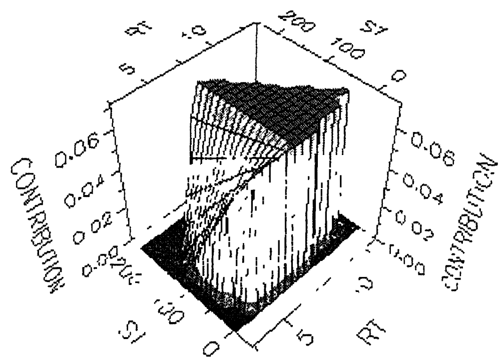
	Variable	Importance	-gcv
3	RT	100.000	0.001
5	MIXING_T	97 617	0.001
8	ST	89.454	0.001
4	MIXER_TE	57.482	0 001
1	CTI	53.243	0 001
2	GHDT	0.000	0.001
6	MIX_TEMP	0.000	0 001
7	PMT	0.000	0.001
9	NO_OF_RO	0.000	0 001
10	FP	0.000	0.001

CURVES AND SURFACES
===================

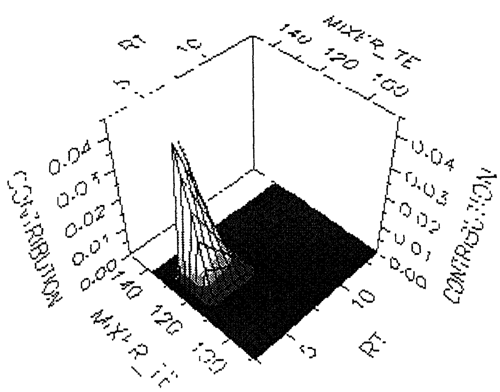
Curve 1 Pure Ordinal



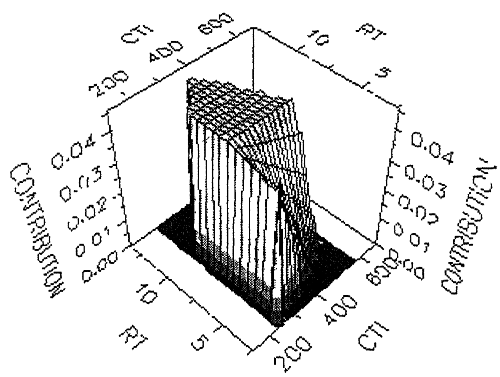
Surface 1 Pure Ordinal



Surface 2 Pure Ordinal



Surface 3 Pure Ordinal



APPENDIX J

DECISION TREE USING ID3 ON TABLE E2

Consider table E2 of Appendix E The Decision Tree is obtained using following steps·

Total Records = 86

STEP 1

First we find the Prior Probabilities of each of the attributes as follows·

PROBABILITIES	CCT	GHDT	RT	MT	MTM	MIX	PMT	ST	ROLLS	FP	GBD
VERY LOW	0	0	0	0	0	0	7	0	0	0	8
LOW	30	32	37	21	16	27	15	32	49	24	11
MEDIUM	24	33	19	36	56	37	41	36	37	39	38
HIGH	32	21	30	29	14	22	19	18	0	23	24
VERY HIGH	0	0	0	0	0	0	4	0	0	0	5

Table J1: Prior Probabilities from table E2

From the above table we have for CCT:

P (CCT=low) = 30

P (CCT= medium) = 24

P (CCT= high) = 32

STEP 2

Now we calculate the probabilities of each column with respect to GBD as follows:

FOR CCT

P (GBD is very high when CCT is low) = 1

P (GBD is high when CCT is low) = 11

P (GBD is medium when CCT is low) = 12

P (GBD is low when CCT is low) = 5

P (GBD is very low when CCT is low) = 1

P (GBD is very high when CCT is medium) = 2

P (GBD is high when CCT is medium) = 9

P (GBD is medium when CCT is medium) = 8

P (GBD is low when CCT is medium) = 1

P (GBD is very low when CCT is medium) = 4

P (GBD is very high when CCT is high) = 2

P (GBD is high when CCT is hıgh) = 4

P (GBD is medium when CCT is hıgh) = 18

P (GBD is low when CCT is hıgh) = 5

P (GBD is very low when CCT is high) = 3

Now we use equation 3.1 (reproduced here for convenience)

$$H(C \mid A_k) = \sum_{j=1}^{M_k} p(a_{k,j}) * \left[- \sum_{i=1}^{N} p(c_i \mid a_{k,j}) * \log_2 p(c_i \mid a_{k,j}) \right]$$

and calculate entropy of CCT with respect to GBD

H (GBD | CCT) = 30/86[- (1/30) * $\log_2$ (1/30) - (11/30) * $\log_2$ (11/30) - (12/30) * $\log_2$ (12/30) - (5/30) * $\log_2$ (5/30) - (1/30) * $\log_2$ (1/30)]
+ 24/86[- (2/24) * $\log_2$ (2/24) - (9/24) * $\log_2$ (9/24) - (8/24) * $\log_2$ (8/24) -(1/24) * $\log_2$ (1/24) - (4/24) * $\log_2$ (4/24)]
+ 32/86[- (2/32) * $\log_2$ (2/32) - (4/32) * $\log_2$ (4/32) - (18/32) * $\log_2$ (18/32) -(5/32) * $\log_2$ (5/32) - (3/32) * $\log_2$ (3/32)]

= 1.867563

Sımilarly we calculate the entropy for each of the attribute and get

H (GBD | GHDT) = 1.892724

H (GBD | RT) = 1 886076

H (GBD | MT) = 1.886028

H (GBD | MTM) = 1 844198

H (GBD | MIX) = 1.875055

H (GBD | PMT) = 1.852493

H (GBD | ST) = 1.863972

H (GBD | ROLLS) = 1.963189

H (GBD | FP) = 1.920326

We find from step 2 that the entropy of Mixing Time (MTM) is the lowest. Thus we form the level 1 of the tree as shown in figure J2 by making MTM as the first node.

STEP 3

Now we rearrange table E1 for attribute MTM = HIGH as shown in table J2.

MTM	CCT	GHDT	RT	MT	MIX	PMT	ST	ROLLS	FP	GBD
high	medium	medium	medium	low	low	very_low	medium	low	low	very_low
high	low	medium	high	high	medium	medium	high	low	high	medium
high	high	high	low	high	medium	medium	medium	medium	high	medium
high	high	low	low	high	medium	low	low	medium	low	medium
high	medium	low	high	high	high	medium	medium	medium	low	very_low
high	medium	high	low	low	low	very_low	low	low	medium	medium
high	high	low	low	high	high	medium	high	low	medium	very_low
high	medium	medium	high	medium	medium	high	medium	low	low	very_high
high	high	medium	medium	medium	high	high	low	medium	low	medium
high	medium	high	high	low	low	very_low	low	low	medium	high
high	medium	low	high	medium	low	medium	low	medium	high	very_low
high	medium	low	high	high	high	very_high	low	medium	low	medium
high	low	low	high	high	high	very_high	low	medium	medium	medium
high	low	low	high	high	high	very_high	medium	low	medium	low

Table J2: Table E2 rearranged with MTM = High

Now we repeat the procedure in step 1 onwards and calculate the entropy of each attribute with respect to GBD.

H (GBD | CCT) = 1.349756925

H (GBD | GHDT) = 1 349756925

H (GBD | RT) = 1.606444643

H (GBD | MT) = 1 421438181

H (GBD | MIX) = 1.285714286

H (GBD | PMT) = 1.026037713

H (GBD | ST) = 1.403677461

H (GBD | ROLLS) = 1.54952346

H (GBD | FP) = 1.508529677

Thus we find that the entropy of PMT is the lowest and place it at MTM=HIGH as level 2 of tree as shown in figure J2 Similarly we form tables for MTM=MEDIUM and MTM=LOW and proceed in the same way to obtain nodes at level 2 for MTM= MEDIUM and MTM=LOW. To construct the tree we proceed with MTM=HIGH. Other nodes can be obtained in a similar fashion.

We break the tree shown in Table J2 with PMT = VERY HIGH, HIGH and so on to get the following breakup as shown in Table J3

PMT	CCT	GHDT	RT	MT	MIX	ST	ROLLS	FP	GBD
high	medium	medium	high	medium	medium	medium	low	low	very_high
high	high	medium	medium	medium	high	low	medium	low	medium

PMT	CCT	GHDT	RT	MT	MIX	ST	ROLLS	FP	GBD
low	high	low	low	high	medium	low	medium	low	medium

PMT	CCT	GHDT	RT	MT	MIX	ST	ROLLS	FP	GBD
medium	low	medium	high	high	medium	high	low	high	medium
medium	high	high	low	high	medium	medium	medium	high	medium
medium	medium	low	high	high	high	medium	medium	low	very_low
medium	high	low	low	high	high	high	low	medium	very_low
medium	medium	low	high	medium	low	low	medium	high	very_low

PMT	CCT	GHDT	RT	MT	MIX	ST	ROLLS	FP	GBD
very_high	medium	low	high	high	high	low	medium	low	medium
very_high	low	low	high	high	high	low	medium	medium	medium
very_high	low	low	high	high	high	medium	low	medium	low

PMT	CCT	GHDT	RT	MT	MIX	ST	ROLLS	FP	GBD
very_low	medium	medium	medium	low	low	medium	low	low	very_low
very_low	medium	high	low	low	low	low	low	medium	medium
very_low	medium	high	high	low	low	low	low	medium	high

Table J3: Breaking up and rearranging of Table J2 using PMT

Now from above table we can again follow the procedure in step 1 onwards or as seen from the table, we make the following observations to make the tree for MTM=HIGH.

(a) From PMT=HIGH

- If GHDT=MEDIUM and MT=MEDIUM and FP=LOW and CCT =MEDIUM then GBD=VERY HIGH
- If GHDT=MEDIUM and MT=MEDIUM and FP=LOW and CCT =HIGH then GBD=MEDIUM

We can also write RT= high instead of CCT= Medium in first rule and RT=medium instead of CCT=high in second rule and so on. However the program will pick up the first entry where the class is conclusive.

(b) From PMT=HIGH we directly get GBD=MEDIUM.

(c) From PMT=MEDIUM we get

- If (GHDT=MEDIUM or GHDT=HIGH) then GBD=MEDIUM
- If GHDT=LOW then GBD=MEDIUM

(d) From PMT=VERY HIGH we get

- If ST=LOW then GBD=MEDIUM
- If ST=MEDIUM then GBD=LOW

OR instead of the two rules above we can have other options like

- If ROLLS=MEDIUM then GBD=MEDIUM
- If ROLLS=LOW then GBD=LOW

(d) From PMT=VERY LOW we get

- If CCT=MEDIUM and GHDT=MEDIUM then GBD=VERY LOW
- If CCT=MEDIUM and MT=MIX=ST=ROLLS=LOW and FP=MEDIUM and RT=LOW then GBD=MEDIUM
- If CCT=MEDIUM and MT=MIX=ST=ROLLS=LOW and FP=MEDIUM and RT=HIGH then GBD=HIGH

If we compare the above rule with the ID3 program output we see that it matches the first part with MTM=HIGH in figure E1 of appendix E.

```
MTM = H  & PMT = L  ==> CLASS = M
           PMT = H  &  GHDT = M  &  MT = M  &  FP = L  &  CCT = M  ==> CLASS = VH
                                                           CCT = H  ==> CLASS = M
           PMT = VL  &  CCT = M  &  GHDT = M  ==> CLASS = VL
                                 GHDT = H  &  MT = L  &  MIX = L  &  ST = L  &  ROLLS = L  &  FP = M  &  RT = L  ==> CLASS = M
                                                                                                      RT = H  ==> CLASS = H
             PMT = M  &  GHDT = M  ==> CLASS = M
                         GHDT = H  ==> CLASS = M
                         GHDT = L  ==> CLASS = VL

            PMT = VH  &  ST = L  ==> CLASS = M
                         ST = M  ==> CLASS = L
```

Figure J1: Program output for ID3 tree for MTM=HIGH

The final step is now to complete the decision tree as shown in figure J2.

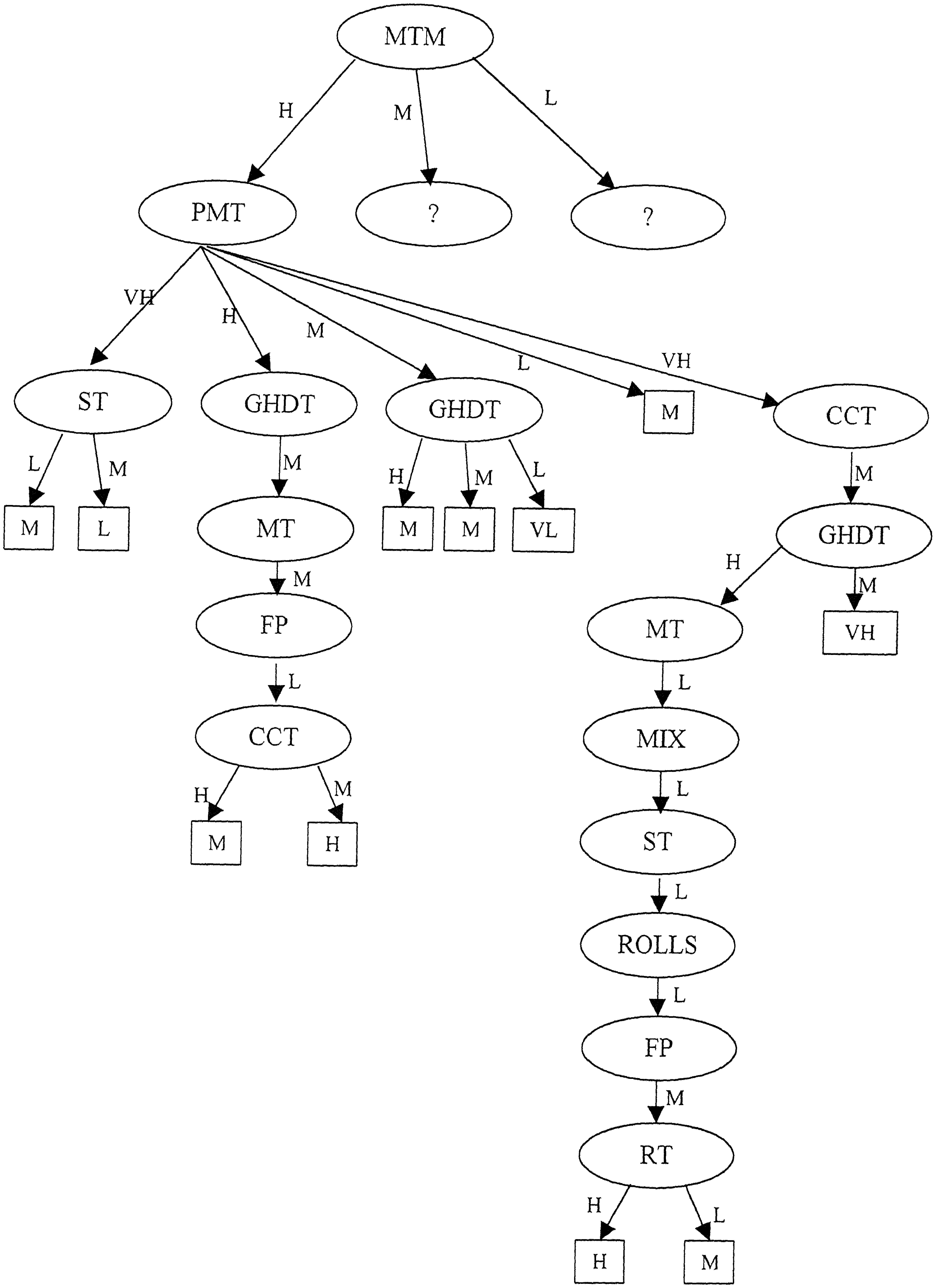


Figure J2: Decision Tree for MTM=High using ID3 Algorithm on rules of table E2

APPENDIX K

SAMPLE PROGRAM STRUCTURE

This appendix explains the general structure and working of program. As the code is quite lengthy, only relevant portion of the code for obtaining Grain Temperature from module-1 is explained. For running module-1 we have to open the "start.ksl" file and compile it.

```
action run;
        do initialise                          % initialises workspace
        and ensure_loaded('sail.ksl')          % loads and compiles (sail.ksl)
        and ensure_loaded('start2.ksl')        % compiles (start2.ksl)
                                               % after initialising loads back run command
        and run_all                            % this is action for (sail ksl)
```

On giving the **run** command on the command window the workspace is initialized and another two files named "start2.ksl" (replica of "start.ksl", as workspace is initialized to clear memory) and "sail.ksl" are loaded and compiled. The program then runs the "sail.ksl" file and a question called find_out as shown in figure 5.3 is asked.

```
action run_all ;
        do ask find_out                        % asks question given below
        and x1                                 % x1,x2 etc. are different subroutines
        and x2
        and x3
        and x4 .. .. ..                        % Present case matches with action x4

question find_out
        WHAT DO YOU WANT TO FIND ?;            % Refer figure 5.3
        choose one of find_out_group.          % list of choices in figure 5.3

group find_out_group                           % list of choices
        grain_temp,
        mix_temp,
        press_mix_temp,
        green_bd,
        grain_heater_retention_time,
        grain_heater_drum_temp_initial,
        combustion_temperature_initial,
```

```
mixing_time,
mixer_temp . ...
```

Suppose we select Grain Temperature as mentioned in section 5.5.1. Then the following subroutine will start working.

```
action x4;
        do if the answer to find_out is 'grain_temp'                    % compares answer
                then do ask fc_bc                                       % question
                and if the answer to fc_bc is 'forward_chaining'        % compares answer
                then do ensure_loaded( 'grain_temp_fln ksl')            % Loads file
                and run_grain_temp_fln                                  % Action for file
                else do ask short_long                                  % question
                and if the answer to short_long is 'short'              % compares answer
                then do ensure_loaded( 'grain_temp_bc_fln.ksl')         % Loads file
                and run_grain_temp_bc_fln                               % Action for file
                else do ensure_loaded( 'grain_temp_full_bc_fln.ksl') % Loads file
                and run_grain_temp_full_bc_fln                          % Action for file
                end if
                end if
                else do true
                end if.
```

After selection of **action x4** another question called **fc_bc** is asked as shown in figure K1.

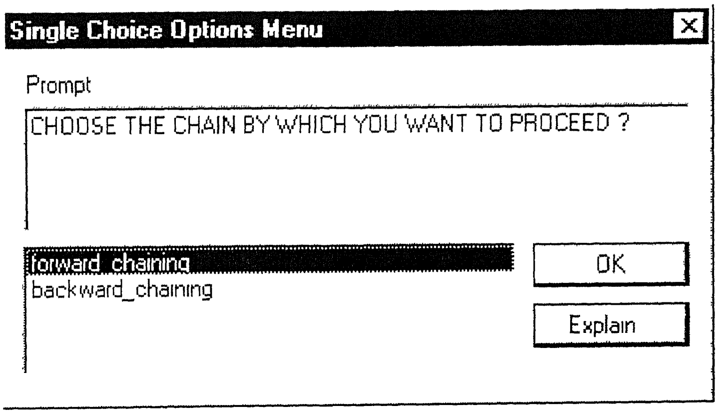


Figure K1: Choosing Forward or Backward chaining

If we select forward chaining, then a file 'grain_temp_fln.ksl' is loaded and compiled. Otherwise backward chaining method is selected and a further question is asked whether to proceed using short method where the inputs will be MIX, MTM and MT or long method where all the inputs from GBD and down below till MT are to be fed. Depending on choice, the concerned program will be loaded and executed. On compilation of

'grain_temp_fln.ksl', the FLINT system along with other files is loaded with the following commands.

```
do ensure_loaded( system(flint) ) .              % This loads the FLINT system
do ensure_loaded( 'attributes.pl ' ) .           % Loads file with membership functions
do ensure_loaded( 'grain_temp_fln_1.pl ' ) .     % Loads the fuzzy rule matrix file
```

The following action takes place.

```
action run_grain_temp_fln ;
        do ask combustion_temp_initial              % question for input
        and ask grain_heater_drum_temp_initial      % question for input
        and ask grain_heater_retention_time         % question for input
        and set_grain_temp                          % calls subroutine
        and putb( 12 )                              % Clears command Window
        and display_grain_temp_values               % calls subroutine
        and gtf                                     % calls subroutine
        and nl                                      % inserts new line

question combustion_temp_initial
        WHAT IS THE INITIAL TEMPERATURE OF COMBUSTION CHAMBER ?,
        input number
```

Then the inputs are fed in the question box shown in figure K2.

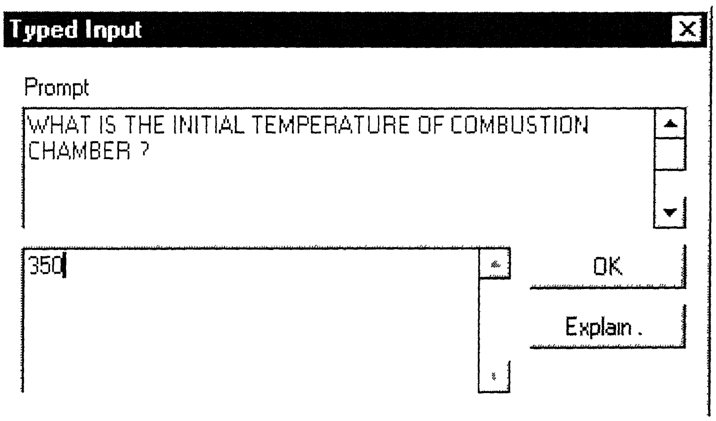


Figure K2: Input for CCT

The explain button will give the message set in the program for the question asked. This is shown in figure K3.

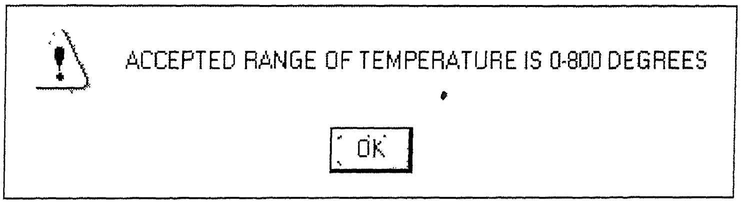


Figure K3. Explain Window

Say we enter the following three inputs

CCT= 350

GHDT= 500

RT = 4.4

The **set grain temperature** subroutine is now called. Variables are assigned with input values and a **relation** is referred to these values for the further process of fuzzification and defuzzification

```
action set_grain_temp
        do  check the combustion_temp_initial is X1                   % assigns X1=350
        and check the grain_heater_drum_temp_initial is X2            % assigns X2=500
        and check the grain_heater_retention_time is X3               % assigns X3=4.4
        and get_grain_temp_value(X1,X2,X3,X4)                         % Calls a relation
        and the grain_temp becomes X4                  % assigns the calculated X4 to GT
```

The following subroutine does all the fuzzification and de-fuzzification process.

```
relation get_grain_temp_value(X1,X2,X3,X4)
        if reset all fuzzy values                            % reset membership values
        and fuzzify the combustion_temp_initial from X1               %fuzzification
        and fuzzify the grain_heater_drum_temp_initial  from X2       %fuzzification
        and fuzzify the grain_heater_retention_time  from X3          %fuzzification
        and propagate grain_temp_value fuzzy rules                    % calls fuzzy matrix
        and defuzzify the grain_temp   to X4 .                        % de-fuzzification
```

The loading of **attributes** file where all the memberships are defined has been done earlier itself. In the first step all the fuzzy values stored from earlier inputs are cleared. Then the first value of 350 is assigned to the membership of CCT defined in the following format.

```
fuzzy_variable(combustion_temp_initial) :-     % format for defining membership ('.pl' file)
  [0,800] ,                                     % Range allowed
  low,                 \, linear, [300,350] ;
  medium,               /\, linear, [300,350,400] ;
  high,                /, linear, [350,400] ;
  centroid(non_zero,extreme,shrink)             % uses centroid method
```

Similarly other attributes are assigned with the input values. The memberships values taken by each of attributes and the rules fired using those attributes is displayed next.

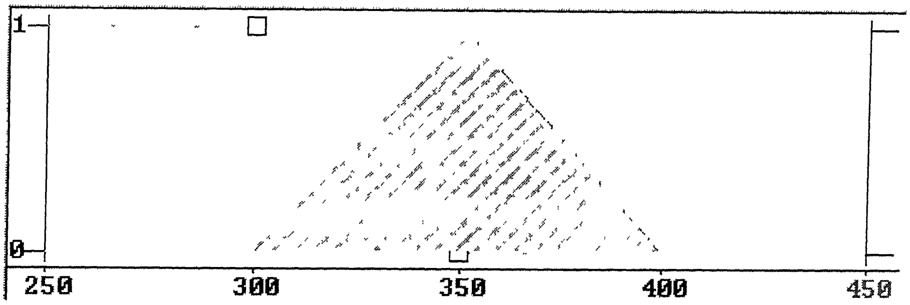


Figure K4: CCT=350 (MEDIUM) with membership=1

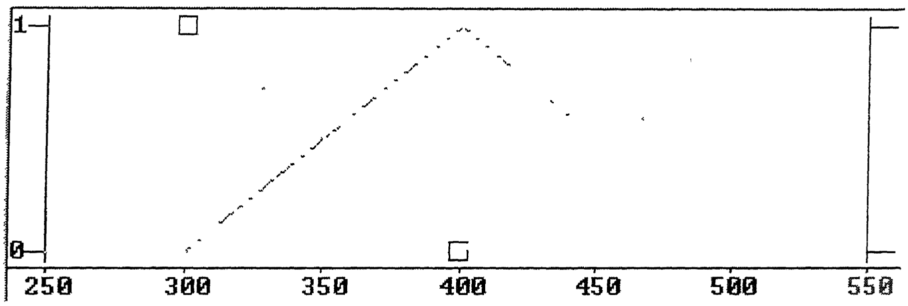


Figure K5· GHDT=500 (HIGH) with membership=1

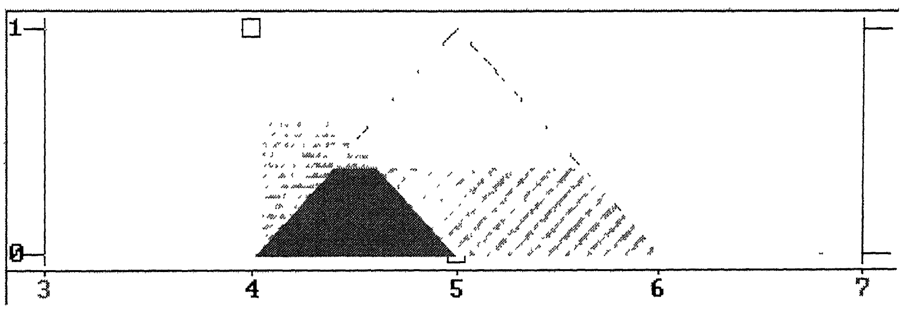


Figure K6: GHDT = 4 4 with LOW and HIGH Membership as shown

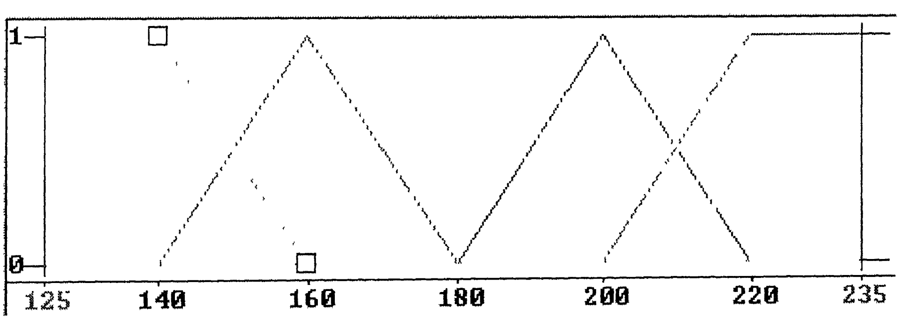


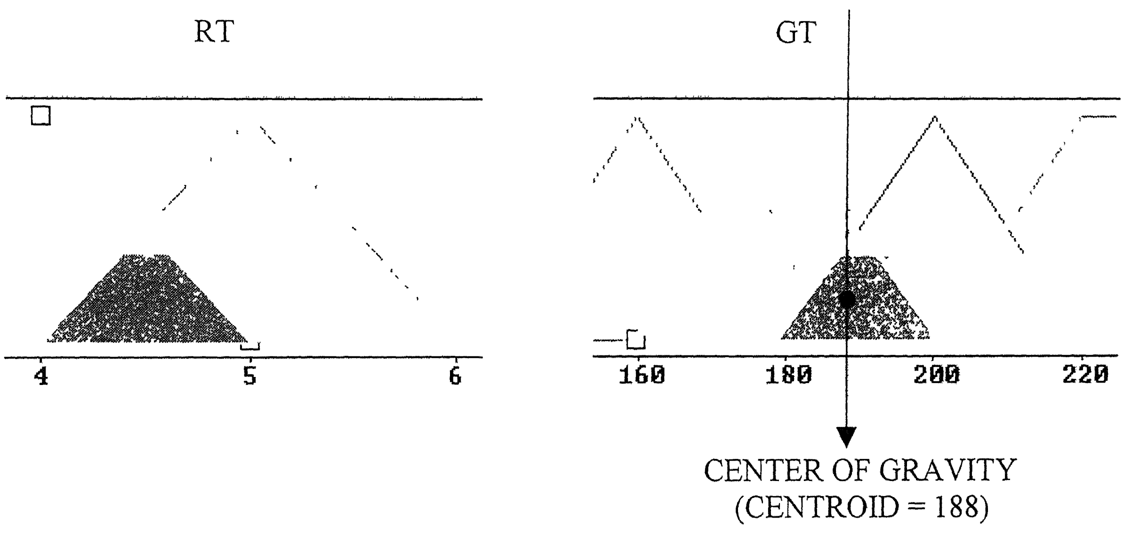
Figure K7· Memberships for GT

Now as we see from figure K4 to K6 the possible rules as called by the program defined in fuzzy matrix '**grain_temp_value**' (refer table B2 of Appendix B) as called through the relation presented earlier are:

- **If** CCT is MEDIUM [1] <u>&</u> GHDT is HIGH [1] <u>&</u> RT is LOW [say 0.6] **Then** GT is MEDIUM. (min membership is 0.6)
- **If** CCT is MEDIUM [1] <u>&</u> GHDT is HIGH [1] <u>&</u> RT is MEDIUM [say 0.4] **Then** GT is HIGH. (min membership is 0.4)

Now as we are using fuzzy operator "&" (MIN) the membership functions fire only the two rules as given above. De-fuzzification is shown in figure K8.

- The membership values from RT = LOW (green shade/horizontal lines) results in GT=MEDIUM (Tan shade/slant lines).
- The membership values from RT = MEDIUM (tan shade/slant lines) results in GT=HIGH (Lavender shade/balls).



<u>Figure K8: De-Fuzzification of Memberships for GT using Centroid Method</u>

Once the areas resulting from firing of rules are obtained, the centroid is found out for the area as shown in figure K8. The overlapping area with two or three colours is considered as many times the overlaps occur. The crisp value of GT is the point on the scale where

centroid lies as shown by arrow. Thus we see that the GT obtained is 188. This value is assigned to variable 'X4' and further to '**grain_temp**' in subroutine '**set_grain_temp**'.

Then the value of GT is displayed as follows

```
action display_grain_temp_values
        do write('The current combustion_temp_initial is: ')
        and write(combustion_temp_initial )
        and nl
        and write('The current grain_heater_drum_temp_initial is: ')
        and write(grain_heater_drum_temp_initial )
        and nl
        and write('The current grain_heater_retention_time is: ')
        and write(grain_heater_retention_time )
        and nl
        and write('The current grain_temp is: ')
        and write(grain_temp)
        and flash('THE GRAIN TEMP IS ',grain_temp,' DEGREE CENTIGRADE')
        and nl .
```

and the result is flashed on the screen as shown in figure K9.

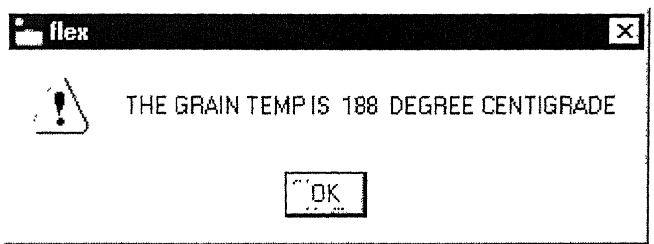


Figure K9. Result of GT

The result is also displayed on the console window as follows:

```
The current combustion_temp_initial is: 350
The current grain_heater_drum_temp_initial is: 500
The current grain_heater_retention_time is: 4.4
The current grain_temp is: 188
```

If instead of centroid method we use peak method, then the membership is defined as follows. The peak membership works only in version 4.2 of Flex.

```
fuzzy_variable(combustion_temp_initial) :-    % format for defining membership ('.pl' file)
  [0,800] ;                                    % Range allowed
  low,              \, linear, [300,350] ;
  medium,            /\, linear, [300,350,400] ;
  high,             /, linear, [350,400] ;
  largest membership                           % uses peak method
```

Considering the same example as for centroid method we see that the crisp value of GT is calculated as shown in figure K10.

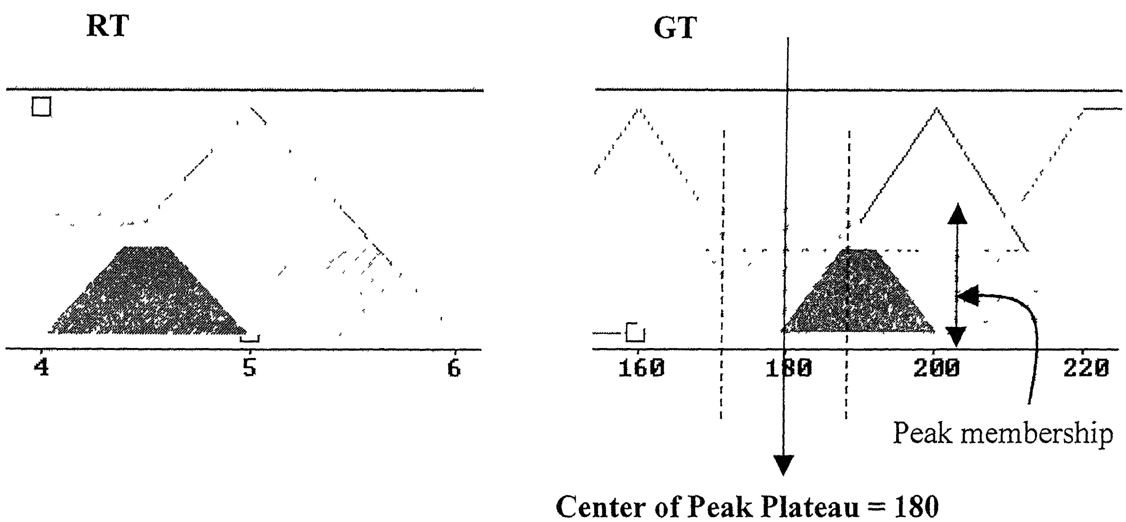


Figure K10. De-Fuzzification of Memberships for GT using Peak Method

The result as given by the program is given accordingly and is shown in figure K11.

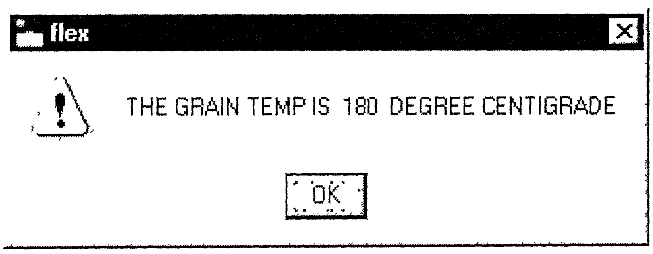


Figure K11: Result of GT using Peak Method